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16. Abstract

This report is the result of a feasibility study to assess the use of artificial intelligence (AI) in alerting the crew of potential emergency situations before they actually occur. The objectives of the project are to specifically determine the feasibility of applying AI methodologies to reduce information overload on the pilot, to monitor data from selected components of an aircraft in flight, to inform the pilot of potentially critical events occurring or materializing, and to advise the pilot of specific actions to be taken in order to delay or avoid potential mishaps.

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EXECUTIVE SUMMARY

The In-Flight Advisor is a hypothetical system designed to help the pilot absorb and integrate flight information collected from many sources. The Advisor should improve the pilot's situation awareness and direct the pilot's attention to impending hazards and possible corrective action. Automated assistance to the pilot has long been studied in the military under titles such as "Pilot's Associate." The In-Flight Advisor addressed in this report is specifically aimed at general aviation.

An interdisciplinary team was assembled at the University of Alabama to study the feasibility and benefits of an In-Flight Advisor system for general aviation. The work was broken into several phases starting with a general feasibility study, progressing through a prototype system, and through evaluation in simulation and in flight.

This is the Phase 1 report. In the context of this phase, the team addressed general issues of the advisor including data collection, human/machine interface, and artificial intelligence methods. Based on these studies, the team concluded that the idea of an In-Flight Advisor for general aviation merits further study. This further activity should include the operational evaluation of working advisor prototypes in simulation and in flight.

The team recommends a specific plan for Phase 2 of the In-Flight Advisor project, as follows: In Phase 2, a prototype Advisor will be implemented in a flight simulator to allow operational evaluation. The scope and functionality of the prototype In-Flight Advisor is outlined in section 2. Section 3 describes the plan for implementing the prototype Advisor in a flight simulator for evaluation.

The remaining sections of the report address specific and separate issues that impact the design of an In-Flight Advisor for general aviation. The team also surveyed the literature and accumulated a large list of papers, which is presented, with abstracts, in the appendix.

The team recommends that Phase 2 of the In-Flight Advisor project be authorized.

1. INTRODUCTION.

1.1 OVERVIEW.

The University of Alabama (UA) assembled an interdisciplinary team to study the feasibility and benefits of an In-Flight Advisor system for general aviation (GA). See tables 1 and 2 for the composition of the team and the areas of expertise represented. The work started on 20 August 1998 and was extended through 15 May 1999. The team surveyed existing literature and studied the issues involved as they applied to general aviation. In conclusion, the team defined the scope and functionality of a prototype advisor and recommended that it be implemented in simulation for further evaluation. The simulation integration and study are suggested for Phase 2 of the In-Flight Advisor project.

TABLE 1. THE IN-FLIGHT ADVISOR TEAM

Name	Title	Affiliation	Relevant Areas of Expertise
Ms. Ellen Bass	Staff Engineer	Search Technology, Inc. (project consultant)	Artificial Intelligence and Applications to Aviation Safety.
Mr. Charles Gainer	New Thrust Coordinator - Marketing	UA Research Laboratory	Aviation, Human Factors
Dr. Amnon Katz	Professor	UA Department of Aerospace Engineering and Mechanics	General Aviation, Flight Training, Flight Simulation.
Dr. Sally McInerny	Associate Professor	UA Department of Mechanical Engineering	Instrumentation, Health and Usage Monitoring.
Dr. Wayne T. Merritt	Associate Professor	UA Department of Industrial Engineering	Flight Operations, Human Factors.

TABLE 2. PILOT EXPERIENCE OF TEAM MEMBERS

Name	Flight Hours Logged	Ratings	Issued by
Ms. Ellen Bass	139	Private Pilot Airplane SEL	FAA
Mr. Charles Gainer	3,250	Aircraft Commander C-47 Rated in B-25, T-6, T-28	USAF
		Commercial Pilot, Airplane SEL, MEL, DC-3 Instrument Airplane Flight Instructor, Airplane SE	FAA
Dr. Amnon Katz	2,700	ATP Airplane SEL, Commercial Privileges Airplane SES, MEL, Rotorcraft Helicopter Flight Instructor, Airplane SE, ME, Instrument Airplane	FAA
Dr. Wayne T. Merritt	1,579	Aircraft Commander B-52	USAF
		Commercial Pilot Airplane MEL Instrument Airplane	FAA

1.2 DATA PRESENTATION.

Some of the more difficult pilot tasks in traditional flying consist of the interpretation of raw information provided by instruments. An Instrument Landing System (ILS) approach is quite demanding when relying on the course deviation needle. It becomes much easier with a Horizontal Situation Display (HSI), which, to some degree, interprets the raw data for the pilot. A moving map display offers even more predigested information and obviates the needs for the marker beacon receiver. A "highway in the sky" heads-up display may do even more.

In another context, reception of two VHF Omnidirectional Radio Range (VOR) stations, in principle, allows the pilot to determine his position. Actually doing this in flight with a pencil on a chart keeps the pilot almost fully occupied for a minute or two. A moving map has this information already processed and allows the pilot's attention to be directed elsewhere. Diverting in flight to a newly selected destination is one of the more difficult tasks required of flight students. It is an iterative process: the aircraft must be turned approximately towards the new destination, time must be noted, and a rough estimated time of arrival (ETA) estimated; then the new course is plotted and measured, and the aircraft heading and ETA are refined accordingly. Finally, time allowing, a wind correction is computed for the new course, and the heading and ETA are further refined. A Global Positioning System (GPS) receiver performs all of this (except steering the aircraft) instantly at the push of a button.

1.3 THE GPS RECEIVER AS AN ADVISOR.

It is probably the coincidence of the widespread use of GPS with the coming of age of computers that should be given credit for the ease with which inexpensive GPS equipment provides fully digested information. In principle, it could have been done with radio beacon receivers and, to some extent, was done by Area Navigation (RNAV) equipment.

The importance of fully worked out information to safety of flight cannot be overstated. When diversion to a new destination is called for in an emergency, the emergency requires the pilot's attention. Being relieved of the burdens of navigation may mean the difference between success or failure.

The current GPS receiver is a very powerful advisor. Its contribution to safety of flight is considerable. The In-Flight Advisor will start with and build upon this existing state of the art. Some of the areas where this is indicated have already been mentioned: e.g., in determining attitude, wind, and airspeed and addressing handling issues. The technologies accessed for this purpose are GPS extensions [1] and wind filtering [2]. Other techniques, usually classified collectively as Artificial Intelligence (AI), may also be brought to bear.

1.4 PLAN OF THE REPORT.

Section 2 sets out the details of the suggested prototype In-Flight Advisor. Section 3 describes the proposed simulated implementation. The remaining sections address specific and separate issues and reflect some of the thinking that led to the proposed prototype and its proposed evaluation in a simulated environment. Section 4 addresses instrumentation and the access of the advisor system to aircraft data. Section 5 describes an existing logic shell that could be used for

implementing the advisor software. Section 6 discusses Human Factors considerations. The appendix offers an extensive list of literature, with abstracts, dealing with in-flight automated help.

2. A PROTOTYPE IN-FLIGHT ADVISOR.

2.1 SOURCES OF INFORMATION.

The output of an In-Flight Advisor must be based on information pertaining to the flight. This presents a problem in the context of general aviation. The typical general aviation aircraft, starting with a J-3 Cub and going all the way up to expensive twin engines, has no electronic bus, where information generated by on-board systems can be collected. Rather, all gages and radios are self contained and, individually, generate visual and/or aural cues for the pilot. The prospect of tapping into all of these separate sources of information to make them available to the advisor is a nightmare and a near impossibility.

Happily for pilots and electronics advisors alike, there is a large body of information about the progress of a flight that has become available from a source that is independent of all on-board gages and radios – GPS. A GPS receiver, by the mere force of being located on the aircraft, can generate information about position, altitude, ground speed and ground track, rate of climb and descent, etc. When coupled with a terrain data base, the same system can generate track deviation data for a desired route, glide slope deviation data, warnings about obstruction clearance and about restricted use airspace, estimated time of arrival, and data for diversion to a different destination.

Extensions and variations of GPS are capable of determining the aircraft orientation [1]. Orientation and ground track together make it possible to determine the wind [2]. With the wind in hand, airspeed can be determined.

If the above wealth of information is made available to the Advisor, the latter becomes able to follow the progress of a flight and to monitor the handling of the aircraft without access to the traditional on-board systems. Drawing on these sources, the Advisor can foresee problems and offer advice based on the actual situation. It has no ability to detect malfunctions of the traditional sensors that might be misleading the pilot. An Advisor limited to GPS could not point out to the pilot things such as incorrect setting of the altimeter, ice in the pitot system, or an incorrect frequency set in a radio. But it could warn the pilot about the resulting incorrect handling of the aircraft and wayward progress of the flight.

There are two classes of problems which a GPS-based system could not detect until it is too late: They are the problems related to fuel management and to engine integrity. For this reason, we feel that the Advisor should also have access to the information that is offered to the pilot by the electrical fuel and engine gages. These include, when installed, the fuel quantity, fuel pressure and fuel flow gages, the oil pressure and temperature, the cylinder head temperature and exhaust gas temperature, and the transmission fluid pressure and transmission chip detectors. Tapping into these electrical gages is within the realm of feasibility.

The above discussion leads to the following recommended policy:

POLICY: The information available to the In-Flight Advisor prototype will be limited to that available from standalone GPS and GPS variant systems and from the on-board fuel management and engine monitoring electrical gages.

2.2 OUTPUT OF THE ADVISOR.

The Advisor is an extension of the concept of the flight director, not the autopilot. It has no actuators and takes no independent action to control the aircraft. Its output is visual and aural intended for the pilot. The Advisor outputs may be broadly classified into three categories:

a. Information offered continuously.
b. Answers to pilot's questions.
c. Event driven information and advice.

The boundaries between these categories are blurred. An ordinary GPS receiver usually offers several selectable pages of information. The pilot's selection of the moving map may be viewed as a specific request: "show me where I am," which would fit in Category b. We prefer to interpret it as sorting among the information offered continuously (Category a). Displaying of the nearest airport or the setting of a course to an alternate destination in response to pilot input fall in Category b. Warning about proximity of terrain, obstructions, or airspace requiring clearance belong in Category c. (Notes are clarified following paragraph 2.2.3.)

2.2.1 Information Offered Continuously.

The prototype In-Flight Advisor will process and update the following information continuously. This information will be accessible to the pilot merely by selecting the display page or pages where it is displayed:

- Position (graphically on a moving map display and digitally as longitude and latitude.)*
- Course deviation (graphically by displaying course line on moving map and also as a steering arrow)*
- Estimated time en route (ETE)*
- Fuel reserve
- Height above minimum en route altitude (MEA)

2.2.2 Information Supplied at Pilot's Request.

- Alternate airport data. Pilot enters alternate airport designator. System displays course to named airport on moving map*, shows heading to steer*, ETE*, and fuel reserve for this destination.

- Nearest airport data. Pilot requests nearest airport. System displays three nearest airports on moving map (adjusting map scale if necessary)* and lists their designators*, distance from current position*, ETE*, and fuel reserve.

2.2.3 Event Driven Communications.

The system generates a visual advisory and/or aural alert when any of the following occurs. (The numbers in parentheses indicate the level of severity with 1 being the least severe and 3 the most severe.)

- Fuel reserve for destination falls below the Visual Flight Rules (VFR) or Instrument Flight Rules (IFR) requirement (whichever applies) (1).
- Fuel reserve for destination falls below zero (2).
- Fuel reserve for nearest airport falls below the VFR or IFR requirement (whichever applies) (2).
- Fuel reserve for nearest airport falls below zero (3).
- Restricted airspace penetration expected in 10 minutes (1).
- Restricted airspace penetration expected in 5 minutes (2).
- Restricted airspace penetration expected in 1 minute (3).
- Below MEA and more than 10 nm from origin and from destination (1).
- Below MEA and descending and more than 10 nm from destination (2).
- Less than 1000 ft above ground level (AGL) and more than 3 nm from origin and from destination (1).
- Less than 1000 ft AGL and descending more than 3 nm from destination (2).
- Less than 500 ft AGL and more than 1 nm from origin and from destination (2).
- Less than 500 ft AGL and descending and more than 1 nm from destination (3).
- Obstructions within 1000 ft of projected flight path less than 10 minutes ahead (1).
- Obstructions within 1000 ft of projected flight path less than 5 minutes ahead (2).
- Obstructions within 500 ft of projected flight path less than 1 minute ahead (3).
- Airspeed within 10 knots of redline (1).
- Airspeed within 1 knot of redline (2).

- Airspeed at or above redline (3).
- Excessive pitch attitude (1),(2),(3).
- Excessive bank (1),(2),(3).
- Engine temperatures and pressures out of range (1),(2),(3).
- Low fuel pressure (1),(2),(3).
- Penetration of the height velocity curve ("dead man curve") (1),(2),(3).
- Settling with power (1),(2),(3).

NOTES:

a. Items marked by * are available from existing GPS systems.

b. The numbers mentioned in the criteria above are offered as an illustration. These numbers should be programmable by the system designer, by the aircraft operator, or by the pilot. In some cases no numbers were offered. The notation (1),(2),(3) means that three levels of alert will be defined based on pertinent parameters.

c. The pilot should be able to turn off alerts and warnings due to a particular cause. Example: The system warns the pilot that he is about to penetrate the Delta airspace of his destination. The pilot knows this and has already established radio communications with the destination tower (which the Advisor has no way of knowing). The pilot should be able to cause all further alerts due to the impending penetration of this particular airspace while continuing to approach it to be discontinued.

d. Since the prototype In-Flight Advisor is to be demonstrated in a helicopter simulator, the list includes helicopter specific items such as settling with power and the dead man's curve. Airplane specific issues, such as impending stall, could be similarly addressed.

3. IMPLEMENTATION IN SIMULATION.

3.1 GENERAL CONSIDERATIONS.

The purpose of the prototype In-Flight Advisor is to allow the benefits of the system to be evaluated in an operational environment. The ultimate evaluation must be in flight with actual systems tapping into the wiring of actual aircraft. Evaluation in simulation can address the operational aspects and benefits of the system. Simulation offers a number of distinct advantages:

- Reduced cost.
- Flexibility in setting up scenarios which include weather.
- Ability to place the flight instantly as required.

- Repeatability—conditions, including weather, can be reproduced precisely.
- Ability to record and replay a flight for analysis.

The preference of the team would have been to test the prototype in a light twin simulator. The most common aircraft in general aviation is the airplane, and the light twin represents the mid-range in cost and complexity. However, consideration of budget and economy dictated the use of the existing helicopter simulator in the University of Alabama Flight Dynamics Laboratory (UA FDL). The issues in some emergencies, for instance the ones that require an off airport precautionary landing, are quite different for helicopters. Yet many of the basic issues of navigation, fuel management, and weather are common.

3.2 UA FDL HELICOPTER SIMULATOR.

The UA FDL helicopter simulator has been in operation since 1981 and has been constantly undergoing improvements and upgrades. The hardware, software, architecture, and math models are all developed in-house by a team of faculty and graduate students.

3.2.1 The Math Model.

Since 1994, the UA rotor model has been *bladehelo* [3]—a true blade model that integrates the flapping motion of individual blades and the shaft rotation. The approach is physically based. There are no prescribed motions and no small angle approximations. Discrepancies are studied until they are understood. *Bladehelo*, played a key role in the discovery of *residual bending* [4, 5]. In real time, body motion is computed at about 88 Hz and blade motion at better than 1000 Hz. *Bladehelo* is undergoing upgrades under a separate FAA task [6] to incorporate models of flexible blades and a wake model based on a vortex lattice. However, the simulator considered for implementation of the prototype In-Flight Advisor is limited to rigid rotor blades and uniform inflow, which is adequate for the task at hand. The ground contact model is based on four skid points and permits the practice of slope landings.

3.2.2 The Cab.

The simulator cab is an actual UH-1 cab and the seats and controls are actual UH-1 items. The round instruments have been replaced by three CRTs, which are used to display images of round instruments.

3.2.3 Image Generators and Data Bases.

The image generators are PC workstations with graphic accelerator cards. The software is locally developed based on OpenGL. The data base format is original. The actual data base is fictitious. It includes an airport with four parallel runways as well as roads, lakes, a river with a bridge, a village, and other features. This environment was introduced in the early eighties (using Iris workstations) and has been evolving ever since. A large building with a sloping roof has recently been added for the purpose of practicing slope landings. All surfaces are textured with the exception of sky and water. The image generators run at better than 40 Hz and provide a front view and a side view.

3.2.4 Optics.

The outside images are presented to the pilots through collimated infinity optics. Both pilots have individual front window displays, and the right seat pilot has a side window display. The optics have recently been upgraded with equipment donated by Boeing Huntsville.

3.3 SIMULATOR UPGRADES REQUIRED.

The current helicopter simulator at UA FDL is intended for the study of helicopter dynamics and handling qualities. The focus is on fidelity in helicopter maneuvers such as lifting to hover, hover, hover taxi and air taxi, takeoff, cruise, approach, landings (including slope landings), and autorotations. The current simulator does not include navigation equipment. The current data base does not cover sufficient territory and does not include a sufficient number of airports to accommodate realistic general aviation trip scenarios. The current image generator software does not offer the ability to simulate changes in the scene due to time of day or obstructions to visibility due to weather. All of these will have to be implemented as upgrades to the current simulator. A list of the required upgrades follows.

a. Communication and navigation radios.
b. Time of day lighting (dusk, night,...).
c. Restrictions to visibility (clouds, fog,...).
d. Round earth.
e. Increased range and features in the data base.
f. Engine and transmission monitoring instruments and supporting software.
g. Provisions for the In-Flight Advisor visual and aural outputs.
h. In-Flight Advisor logic software and interface with the simulation host.

4. INSTRUMENTATION ISSUES.

Surveys of the general aviation fleet indicate that single and multiple piston engine aircraft account for over 80% of the GA aircraft and 75% of GA flight hours. See figures 1 through 3, constructed from data available in references 7 and 8. The average age of these piston engine aircraft is 28 years.[7] If the GA accident rate is to be decreased in the near term via changes in instrumentation and advisory systems, these changes will require retrofits and add-ons to piston engine aircraft.

According to reference 7, fuel mismanagement was the cause of 8% of the total number of GA accidents in 1997. Fuel management was the cause of 9.6% of the pilot-related accidents in 1996-1997. Mechanical maintenance problems accounted for close to 14% of the total number of 1996-1997 GA accidents.[8] The largest percentage of these were due to powerplant and/or propeller problems.

The focus of this section is on powerplant instrumentation and monitoring systems that have the potential to reduce the accident rate due to powerplant and fuel management problems. An informal survey of GA instrumentation and instrumentation systems indicates a wide variety of

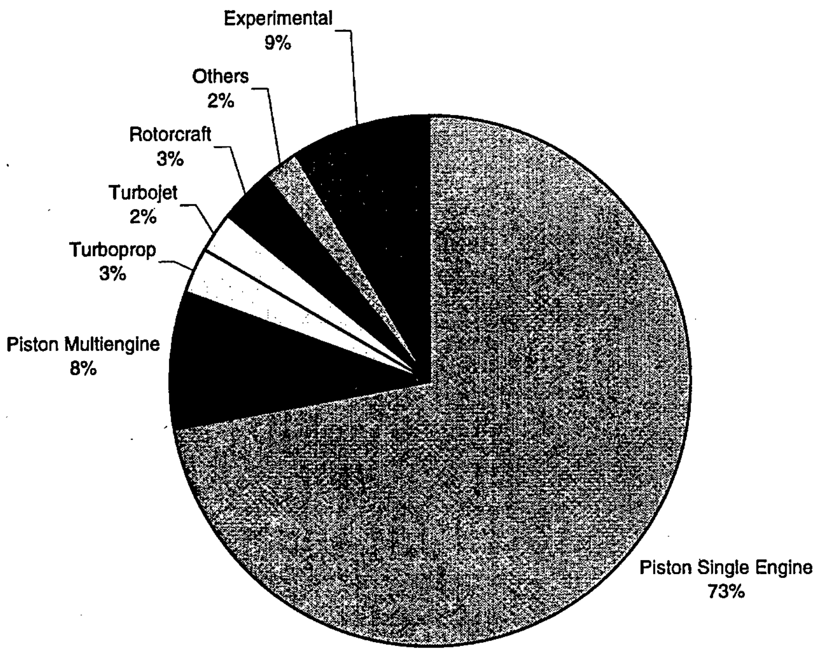

FIGURE 1. ACTIVE GA AIRCRAFT IN 1996 = 187,312

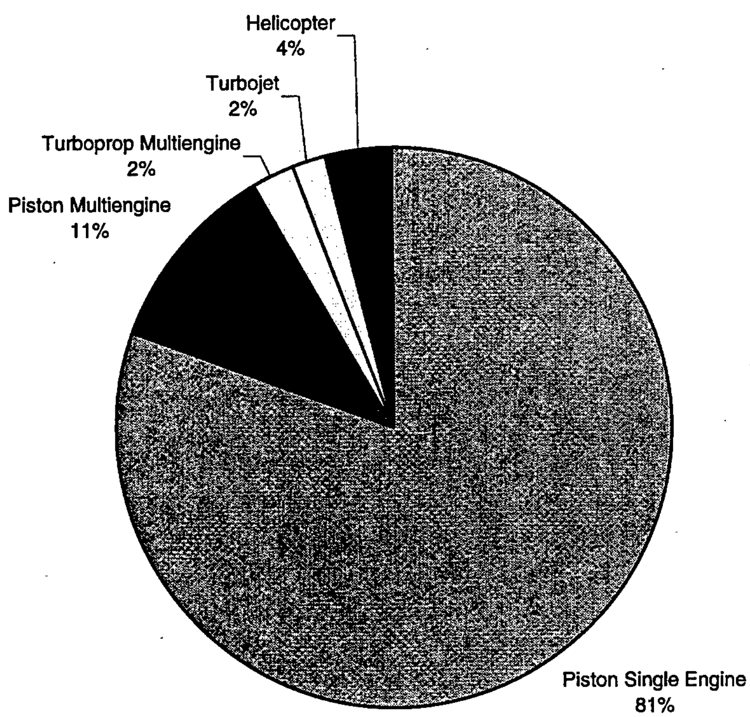

FIGURE 2. NUMBER OF GA AIRCRAFT SURVEYED BY AIRCRAFT OWNERS AND PILOT'S ASSOCIATION IN 1997 = 209,698

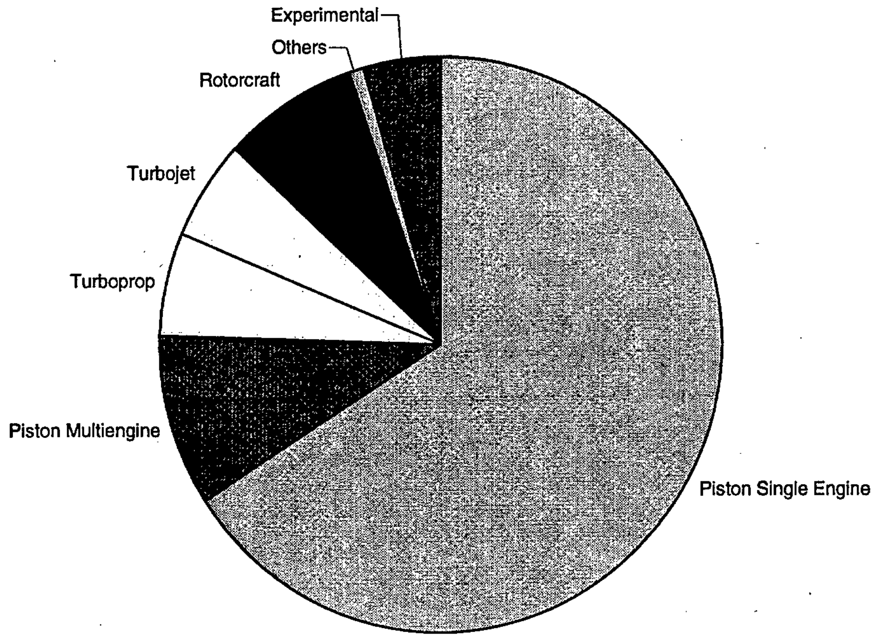

FIGURE 3. GA AIRCRAFT FLIGHT HOURS IN 1996 = 26,100,000

instrumentation and instrumentation systems is available for GA aircraft. The largest category of instrumentation is individual gages and sensors, including:

- Oil Pressure
- Oil Temperature
- Cylinder Head Temperature (CHT)
- Exhaust Gas Temperature (EGT)
- Fuel Quantity
- Fuel Pressure
- Fuel Flow Rate
- Outside Air Temperature
- Hour Meter

While these instruments have the potential to increase the accuracy and amount of information available to the pilot, they require the pilot to continually review and assess the information displayed by the individual gages.

Systems that measure and display two or more measurements are the next step up in instrumentation systems. Typical parameter combinations are:

- CHT and EGT
- Manifold Pressure and Fuel Flow
- CHT, EGT, Oil Pressure, and Oil Temperature
- Tachometer, EGT, Volts, CHT

Instruments are available that scan multiple (e.g., 8 to 16) temperatures displaying a different set every few seconds. These gages are more convenient and take up less space. Reference 9 provides a "Combustion Analyzer Troubleshooting Guide" that suggests probable causes for EGT trends and recommended actions. Two examples are given in table 3.

TABLE 3. EXAMPLES OF TROUBLESHOOTING GUIDANCE

EGT Symptom	Probable Cause	Recommended Action
Fast rise in EGT of one cylinder	Spark plug not firing due to fouling or faulty plug, lead, or distributor	Enrich mixture to return EGT to normal. Go to single mag operation. When magneto firing the bad plug is selected, EGT will drop suddenly, defining which plug is bad
Slow rise in EGT	Burned exhaust valve	Have compression checked

Simple multiple-parameter gages do not synthesize or diagnose (such as in the examples above) the information they display. Neither do they provide alarms, other than redline indicators. Instrumentation systems that provide one or both of these missing features are the next step up. Several such systems with varying degrees of sophistication are discussed below.

4.1 SMART ENGINE ANALYZER FROM ELECTRONICS INTERNATIONAL.

This system has one display and monitors up to eight engine temperatures. The system "automatically scans through its channels memorizing temperatures, calculating temperature spreads, and determines over/under temperature conditions, alerting you the moment a problem occurs." It appears that the alert is a red light [10, pg. 339]. Cost $425.

4.2 FUEL FLOW/PRESSURE INSTRUMENT FROM ELECTRONICS INTERNATIONAL.

This system provides pilot programmable low-fuel alerts and a pilot programmable time-to-empty alert. The alert is a blinking low fuel light-emitting diode (LED). One pilot-programmable low fuel pressure warning and one pilot-programmable high fuel pressure warning are also provided. Fuel pressure and fuel flow sensors can be purchased with the system. "Features include programmable K factor, programmable fuel weight, programmable display for gal. or lbs., fuel flow to 0.1 gal/hr, fuel used and remaining to 1/10 of a gallon, time to empty to one minute, ..." [10, pg. 340]. Cost $755 w/o transducers, $945 with both transducers, and $1085 with transducers and GPS.

4.3 THE ADVANCED ENGINE INFORMATION SYSTEM (EIS) FROM GRAND RAPIDS TECHNOLOGIES, INC.

The EIS is designed for two- and four-stroke engines. The display has six display pages selectable from a button on the display panel. Two combination pages display six to seven engine parameters that are grouped to provide a summary of the engine's condition. The user can program limits (it would appear that only one high or one low limit can be set per parameter). A red warning light is illuminated when a limit is exceeded. A Fuel Flow System Option is available which adds fuel flow rate, total fuel remaining, time until empty, low-fuel

warning, and fuel pressures. Cost of the Advanced EIS with Fuel Flow Option is around $950, but this does not include all of the sensors required for most engines.

4.4 MicroMONITOR FROM ROCKY MOUNTAIN INSTRUMENT.

"The MicroMONITOR has 22 different functions including manifold pressure, tachometer, EGT, CHT, oil temperature, carburetor temperature, ammeter, voltmeter, oil pressure, fuel pressure, and outside air temperature. An integral turbine-sensor fuel totalizer provides fuel flow, fuel quantity remaining, and time to empty tanks. The system constantly monitors critical parameters such as oil and fuel pressure and audibly and visually alerts the pilot of problems." The pilot can select and program the high and low alarm values [11]. Average systems with all transducers are around $1400.

4.5 AV-10 ENGINE MONITOR FROM AUDIO FLIGHT AVIONICS.

The AV-10 Engine Monitor monitors 16 to 24 engine temperatures, EGT/CHT temperature span, oil temperature, oil pressure, and more than 12 other engine parameters. A data logging option is available. The user can program high or low limits and "an appropriate audio message is presented to the pilot via the headset" when a limit is exceeded. The liquid crystal display (LCD) displays only one parameter at a time. The cost of the AV-10 Voice Alerting System is around $1300, with the following options available.

- Two-line LCD $185
- Four-line LCD $225
- Data logging $125
- Fuel flow/totalizer $250

4.6 VM1000 ENGINE INSTRUMENTATION SYSTEM FROM VISION MICRO.

This system combines revolutions per minute (rpm), manifold pressure, oil pressure, fuel temperature, fuel pressure, fuel flow, fuel computer, voltage, amperage, CHT, and EGT. It includes a flight data recorder. Parameters are displayed in an integrated "glass-cockpit" display. The EC-100 option adds an engine caution advisory system and several checklist systems (electronic, aircraft, etc.). "The exclusive 'autotrack mode' tracks engine performance and alerts you to any changes in parameters such as a slow decrease in oil or fuel pressure..." [10, pg. 338]. Cost for 4 cylinders $2995, the following options are available.

- Air temperature system $285
- Fuel level system $384
- ED-100 electronic checklist $540

5. ARTIFICIAL INTELLIGENCE TECHNIQUES.

This section describes an approach to applying artificial intelligence techniques to the problem of human error in general aviation. The approach focuses on averting the negative consequences of hazards rather than preventing pilot errors. Aviation mishaps attributed to human error are more often due to a set of events leading to the mishap rather than one catastrophic event. For

example, increased pilot workload during abnormal, emergency, or poor weather conditions; pilot confusion regarding system behaviors; and too much focus on one part of the system to the detriment of other piloting activities may all contribute to the same accident or incident.

These problems require a strategy to help the general aviation pilot recognize the precursor conditions as they occur so they can be fixed before turning into a mishap. A strategy developed by Search Technology, Inc. is called *hazard monitoring* [Ernst-Fortin et al., 1997 [12]]. It is an aiding concept that helps to avoid operational problems by helping the pilot to recognize a deteriorating situation in time to avoid its adverse consequences. The idea is to aid in these situations by enhancing the problem recognition and identification process.

Hazard Monitor (HM) is a knowledge-based system prototype that helps pilots avoid the disastrous consequences of in-flight hazards. HM unobtrusively monitors the system for potential hazards and notifies the pilot only if it detects a hazard and only if the pilot has not taken steps to avoid that hazard. Because the monitoring system has no controls and only issues notifications when necessary, the pilot can focus on aviating, navigating, and communicating.

5.1 STATEMENT OF THE PROBLEM.

Traditional error prevention strategies (e.g., error prevention based on structured aircraft design, ergonomics, and training) have been followed for decades and were believed to be successful at reducing the total number of aviation accidents due to human error. Pilot training reinforces the proper way to perform the job. Cockpit and software designers attempt to make errors very difficult or impossible to commit. In advanced aircraft, automated systems are designed to help pilots control their aircraft more accurately and provide protection from common hazards (e.g., stalls, mid-air collisions, and controlled flight into terrain). These preventative approaches have been practiced for decades and may have reached their limits of effectiveness in further reducing human error rates. For example, in U.S. commercial aviation over the past thirty-five years, the percentage of serious aircraft accidents due to pilot error has remained near 70% (Boeing, 1998) [13].

Even with good design and human-factors practices and with initial and recurrent pilot training, not all hazards can be prevented. The complexities of the aviation environment are such that hazards will occur. In dealing with the dynamics of the aviation environment, there is no substitute for human judgment, and that is why human pilots are in command of airplanes. But, being human, pilots may not be able to deal with all hazards before they result in unacceptable consequences. Pilots, therefore, need help in dealing with flight hazards, and the available accident and incident statistics indicate that the current forms of help are insufficient.

Part of the problem is that pilots have difficulty achieving and maintaining situation awareness. The literature describes many incidents and accidents (e.g., the 1994 Nagoya airport Airbus crash [Hughes and Dornheim, 1995 [14]]) which could have been avoided if the pilots had recognized a deteriorating situation in time to avoid its adverse consequences (Endsley and Bolstad, 1993 [15]). The reasons for not recognizing an impending problem typically fall into three general categories: system data problems, human limitations, and time-related problems.

System data problems arise despite the careful design and development of computer-human interfaces that include new technologies to help reduce these problems [Endsley, 1993 [16]]. Types of system data problems include:

- Data pertinent to the deteriorating situation are *obscured* by other system data.
- Data are sometimes *hidden* within automated functions.
- Data are sometimes spread across many displays, leaving the operator to *integrate* the data into usable information.

Data are presented at a level of detail that is inappropriate for the tasks being accomplished, leaving the human to *abstract* useful information from a glut of system data [Endsley, 1995 [17]].

Unfortunately, it is not possible to engineer solutions for all situation awareness related problems. Even when system data are complete and available, human limitations may lead to missing the signs that a dangerous situation is developing (e.g., Hughes and Dornheim, 1995 [14]). Some reasons that operators have trouble performing situation assessment relate to features of the work environment, such as high workload (i.e., where several activities are occurring at once (e.g., Anonymous, 1994 [18])) and interruptions (i.e., where primary tasks are interrupted by secondary tasks (e.g., National Transportation Safety Board, 1989 [19])). Other reasons relate to characteristics of human behavior. Such behaviors include the tendency to fixate on the task at hand to the exclusion of others (e.g., National Transportation Safety Board, 1973 [20]) and poor passive system monitoring (Sheridan, 1992 [21]).

Another element of the situation assessment problem in complex systems is dynamic-state data. This behavior adds to the difficulty of detecting potentially dangerous system states because it requires that data monitoring and interpretation be exercised repeatedly over time, further reducing the likelihood of it being done properly. The need to monitor particular data among all the system states during that period compounds this problem.

5.2 SOLUTION TO THE PROBLEM.

A strategy to augment pilot situation awareness and judgment is Search Technology's *hazard monitoring*. Search Technology's Hazard Monitor (HM) is an innovative, system-wide approach to solving the problem of preventable incident and accident rates. HM is intended to complement the traditional approaches to error prevention—not to supplant them—by operating in tandem with existing automation. As a research prototype, HM unobtrusively monitors the system for potential hazards and notifies the pilots only if it detects a hazard and only if the pilots have not taken steps to avoid that hazard.

The proposed Hazard Monitor detects hazards as discrepancies in expected performance and offers remedies for the discrepancies based on their likely consequences. Preventing consequences, rather than errors, strikes at the heart of the operational safety problem: improving safety by anticipating and preventing accidents. Pilots, though well-trained experts, are still human; so, they will always encounter hazardous situations that tax their abilities to

safely recover. HM mitigates the effects of those inevitable hazards. This goal of avoiding the negative consequences of hazards is accomplished through three important innovations: a pilot-centered philosophy, context sensitivity, and persistence.

5.3 PILOT-CENTERED PHILOSOPHY.

Our pilot-centered approach evolved out of extensive previous work in the fields of human factors, systems engineering, and pilot-vehicle interface research (c.f., Hammer and Small, 1995 [22]). This underlying philosophy dictates that the purpose of automation in the cockpit is to help the pilot, not to do the job for him. Therefore, the purpose of hazard monitoring is to detect a hazardous situation and to notify the pilot of the hazard so that he can act to remedy the situation before unacceptable consequences occur. It imposes no extra physical workload on the pilot because it requires no direct manipulation and issues notifications only when necessary; that is, only if it detects a hazard and only if the pilot has not taken steps to avoid that hazard.

Another important distinction of the pilot-centered philosophy is that HM does not attempt to attribute cause. HM must detect a hazardous situation whether it is due to pilot error or to some other cause. It only slows HM processing to first identify the hazard's cause before providing advice to the pilot about how to avoid that hazard.

5.4 CONTEXT SENSITIVITY.

Traditional error prevention strategies typically reference a small number of inputs in their decision-making. For example, the interlock mechanism that prevents the pilot from raising the landing gear while on the ground is based solely on the weight-on-wheels sensor. The failure of this single sensor could lead to costly or deadly consequences. A decision process based on a single input is ill-equipped to produce correct responses when faced with complex events. The Hazard Monitor may employ a small set of inputs or it can use a much richer set of inputs. To continue the example, information about aircraft motion, altitude, state of the engines, and so on could be added to the weight-on-wheels condition to help prevent a gear-up landing due to a premature wheel retraction during a touch-and-go landing when the aircraft is airborne but fails to sustain a positive rate of climb due to an engine failure. This richer set of inputs enables HM to take a more complete approach to detecting and avoiding hazards, instead of treating each error or hazard as a special case.

Employing a richer set of inputs also facilitates a greater specificity of the discrepancy notifications, and it allows a more robust set of notification levels. With greater knowledge of the surrounding conditions discrepancy notifications provide clear remedial directives (e.g., extend gear) with sufficient contextual detail to clarify its purpose (e.g., due to loss of altitude during touch-and-go). Under less urgent conditions such detail will contribute to a pilot's trust in the system by providing a mechanism for examining its reasoning process. Greater situational awareness enables HM to modify its notifications based on the urgency (i.e., the relative temporal proximity to the negative consequence) and the severity (i.e., the relative assessment of the negative impact of the consequences) of the impending hazard. The more urgent or severe the situation, the more forceful HM can be with its notifications—and vice versa.

5.5 PERSISTENCE.

The third distinction of HM from other automated systems is that HM exhibits a special behavior—persistence. When a traditional automated system detects a hazard, its behavior falls into one of two categories: it notifies the pilots immediately, then ignores the situation; or, at the other extreme, it constantly alerts the pilots to the problem regardless of how the situation is evolving. (Pilots disdainfully nickname automation that exhibits this latter behavior "Bitching Betty.") HM, in contrast, continues to monitor the evolving situation, adjusting its behaviors accordingly, and appropriately notifying the pilot of the hazard until the hazardous situation is resolved. The advantage of HM is that it serves as an *extra set of eyes* that has electronic access to all available state data; but, it is never over-burdened, is not socially inhibited, and never grows tired of monitoring.

In summary, the purpose of hazard monitoring is to detect a hazardous situation and to notify the pilots of the hazard so that they can act to remedy the situation before unacceptable consequences occur. The technical challenge for HM is to consistently recognize real hazards (i.e., developing situations with unacceptable consequences) and to notify pilots in a timely, context-sensitive manner while avoiding false or unnecessary alerts.

5.6 SUGGESTED TASKING FOR TUNING THE IN-FLIGHT ADVISOR PROTOTYPE.

The following tasks are suggested as logical steps for tuning the proposed In-Flight Advisor.

5.6.1 Scenarios.

The In-Flight Advisor team must design scenarios that can illustrate compelling operational and market reasons for adopting the In-Flight Advisor technology. The scenarios must identify the hazard set that the In-Flight Advisor prototype will address.

5.6.2 Knowledge Engineering.

HM knowledge engineering involves embodying the knowledge within structures called *expectation networks.* It also requires definition of parameter bandwidths for monitoring. University of Alabama engineers will assess the availability of the desired state data; that is, they will determine which data are available in the simulator. Although HM has a state assessment module, this task does not include identifying any high-level state assessments that may be required. University of Alabama will accomplish any required assessments.

5.6.3 Knowledge Base Development.

This task involves implementing the knowledge base needed by HM to monitor hazards.

5.6.4 Integration.

Search Technology will help University of Alabama engineers to integrate HM into the simulation environment. The simulation environment provides the state data needed by HM to track the evolving hazards. As part of this task, Search Technology and University of Alabama

will determine how the HM process will communicate with the simulator to obtain system states. Preferably, University of Alabama will provide wrapper functions around available interprocess communication mechanisms to obtain the required states.

Similarly, HM's output messages must be available in a suitable format to the aircraft simulation environment. Preferably the University of Alabama engineers will develop display software that can interpret HM's existing output. Search Technology will provide a prototype implementation of a generic Advisory, Caution, and Warning System (ACAWS) display to expedite University of Alabama's efforts.

5.6.5 Testing.

This task involves verifying the HM software. This means ensuring that the HM software and networks process simulated state data as expected in response to the scenario events.

5.6.6 Documentation.

This task involves preparing inputs for reports as required by the University of Alabama.

6. PILOT/SYSTEM INTERFACE.

6.1 INTRODUCTION.

In recent years, technological advancements in the cockpit have changed the nature of the piloting tasks in the air carrier context. These technological advancements include automation, glass-cockpit interfaces, and intelligent cockpit assistants. The technological components of air carrier systems are more reliable and safer. Even with these improvements, however, the rate of airline accidents has remained at a near constant level for a number of years. Moreover, human error has remained a contributor to approximately 75 to 80 percent of air carrier accidents. Accidents that have been avoided with the advent of the automated cockpit have somewhat been replaced by accidents that result from the human use of the automation.

The total number of air carrier flights is expected to double over the next decade. If the rate of air carrier accidents remains the same, then the absolute number of accidents will also double. For the flying public to maintain confidence in the safety of aviation, the rate of accidents must be reduced. Consequently, the Federal Aviation Administration (FAA) has placed a high priority on the reduction of the human contribution to the accident rate. This has taken the form of a national priority initiative in the implementation of human factors in the design of air carrier flight decks.

Efforts by the FAA, National Aeronautics and Space Administration (NASA), and several universities have brought the need for human factors in design of aviation systems to the forefront. Even though human factors has been recognized as important in aviation systems since World War II, there is much left to be learned about properly incorporating human factors in design efforts. Many problems have been addressed and studied. Among these are the fundamental nature of human error, display interface design issues, pilots' mental models of aviation systems, and the nature of the way humans interact with automation. However, much

remains to be learned about these issues. There are many interface design issues that have been learned empirically, but the human factors community is far removed in being able to provide quantitative analytical techniques for designs that have a significant human component.

General aviation has not benefited to a great degree from technological improvements. Most general aviation cockpits are still designed around the "round dial" concept, where each instrument provides a single piece of data, all of which must be integrated in the mind of the pilot into a workable mental concept of the present position of the aircraft and of its predicted position. Coupled with the fact that many general aviation pilots who fly in the weather have minimal opportunity to refine their instrument flying skills, there is a significant potential for human error accidents. The problem of a lack of situational awareness can be very acute for the marginally proficient general aviation pilot flying in instrumented meteorological conditions (IMC), who encounters an emergency or unexpected weather during his flight.

Free flight is on the horizon. Free flight places more responsibility on the pilot for navigation and traffic clearance and may place a greater mental workload burden on the general aviation pilot. In addition, the FAA and NASA are encouraging more general aviation usage to take some of the burden off the expected demand on the air carrier system. There is a need for improved general aviation cockpit systems to reduce the mental workload of the potentially overloaded general aviation pilot. The GA In-Flight Advisor system that is the subject of this report is expected to assist the general aviation pilot in maintaining situation awareness and reducing pilot mental workload.

6.2 PURPOSE.

The purpose of this section is to review recommendations and current research related to design of the human-system interface in the general aviation cockpit. Because of the lack of research and recommendations relating specifically to general aviation, findings in the air carrier and military contexts will be reviewed and related to the current effort. The context of this review is as a preliminary effort for the design of an In-Flight Cockpit Advisor for general aviation pilots. The advisor addressed here is the prototype In-Flight Advisor defined in section 2.

Work has already begun to design and implement an integrated general aviation cockpit. The National Aeronautics and Space Administration (NASA) has implemented the Advanced General Aviation Transport Experiments (AGATE) program, demonstrating its commitment to reviving the general aviation industry [Gorder and Uhlarik, 1995 [23]]. Available inexpensive technologies will enable design and implementation of highly automated operation in the general aviation aircraft. Suggested primary flight displays would have several modes of operation, including a plan mode for flight planning and navigation, an area mode displaying electronic maps and aircraft position relative to other entities such as weather, and a configuration mode used to configure other displays and control the level of automation that is operational at any point in time. Ideally, the integrated cockpit should provide a human-machine interface that simultaneously reduces mental workload and enhances situation awareness [Gorder and Uhlarik, 1995 [23]]. However, mode awareness problems have been found to add their own potential for human error, increase in mental workload, and a reduction in situation awareness [Sarter and Woods, 1995 [24]]. As a result, design of new general aviation cockpits should draw upon the experiences of implementation of automation in the air carrier and military contexts.

The Cirrus SR-20, a general aviation aircraft with an advanced cockpit design with multifunctional displays based on the AGATE cockpit concepts, has already been certificated. As experience is gained with this and other advanced cockpit GA aircraft, the effectiveness of the automated GA cockpit will increase, and such systems will be installed in more new aircraft. However, the many existing general aviation aircraft will continue to fly with existing, traditional cockpit layouts. The In-Flight Advisor could be configured as a carry-on device, much like a laptop computer, or it could be installed in the cockpit as a permanent fixture.

6.3 HUMAN ERROR IN DESIGN.

Human error is implicated as a contributing factor in a majority of aircraft accidents. Traditionally, error prevention has been attempted through structured design, ergonomics, automation, personnel selection, and extensive training. Initially, this approach successfully reduced the total number of aviation accidents due to human error. However, for the past 30 years the percentage of air carrier accidents due to pilot error has remained near 75%. The recent trend, to replace human action and judgment with automation intended to prevent error, has merely shifted human-system error from direct aircraft control to control of the automated systems [Greenberg et al., 1995 [25]].

It has been suggested that the design of the flight deck can actually cause humans to err. Many of the errors that have been committed are common examples of human behavior—not abnormal or erroneous behavior. Designers of systems often expect humans to act in unnatural ways, that is to say, not to be prone to these natural behaviors. In the aviation industry, these behavioral tendencies are often not considered in the design of human-machine interfaces. In aviation accident investigations, the causal factor for the accident is often attributed to flight crew error rather than being attributed to the designs. Consequently, humans are assigned blame for being human—for acting naturally. NASA Langley Research Center has implemented a research program that seeks to develop a human-centered flight deck design guided by a philosophy that humans and machines are complementary and that the safety and efficiency of flight will be maximized when this complementary nature is supported by the design. The program is called "Error Proof Flight Deck," a title that emerged from the fact that human error is inevitable [Schutte and Willshire, 1997 [26]].

Greenberg et al., 1995 [25] suggest that a new perspective on error is needed. Errors are often considered failures of the operator, but prejudging certain acts to be errors is not helpful for improving the operator's performance. It is more constructive to consider that errors reflect flaws in the design of the human-machine system. Greenberg et al., 1995 [25] believe that it is not only impossible to prevent all errors, and their research has revealed that it is unnecessary and even undesirable to identify, prevent, and correct all error. Most errors have few, if any, negative consequences. They state that *the term error itself is an interpretation in hindsight;* an error is significant only if negative consequences follow. Human centered systems should be forgiving. The system should provide error feedback to aid recognition, and pilots should be trained to recognize and acknowledge mistakes (freeing them to take remedial action) to mitigate the impact of error.

Greenberg et al., 1995 [25] also state that there are two approaches to dealing with human error through automation: error prevention and error tolerance. Error prevention, the traditional approach, now extends beyond personnel selection, training, and traditional human factors design into human reliability design. Human reliability design identifies error prone behaviors and mechanisms and then designs interlocks and redundant systems. Further robustness can be gained by designing systems that are error tolerant. Because humans are naturally going to make mistakes, error tolerance should be a systems design goal. A guiding principle for error tolerant design is that errors are not the real problem, but rather the consequences that follow from them. Therefore, it is desirable to eliminate the undesirable consequences of error, not the errors themselves [Rouse, 1985 [27]].

Errors tend to be cumulative and not necessarily contiguous. An error made at one point in a flight may show up, for example, as a mode error when the aircraft fails to make a scheduled altitude change. Telling the pilot about the earlier mode error does not give him direct guidance about how to correct the combination problem he is now facing, that is, correcting the current altitude deviation. Pilots generally prefer getting corrective advice to being told about their errors [Greenberg, et al., 1995 [25]]. For the In-Flight Advisor, a desirable design objective is to monitor errors within the context of the total flight environment and provide advice and intervention strategies to aid the pilot in neutralizing the cumulative effect of errors and other deteriorating flight conditions.

6.4 FAA HUMAN FACTORS TEAM REPORT ON HUMAN FACTORS IN AUTOMATION.

The FAA has found that even though highly automated transport aircraft have demonstrated an improved safety record relative to the previous generation of aircraft, vulnerabilities still exist. These vulnerabilities primarily reside in the flight crew/automation interface. To strive for a goal of zero accidents, the FAA chartered a human factors (HF) team to address human factors issues related to the modern automated aircraft. The report of the HF team, *The Interfaces Between Flightcrews and Modern Flight Deck Systems*, FAA, 1996 [28] is the source for the information in this section.

The human factors team of experts was chartered to evaluate the modern transport category airplane flight deck designs in regard to the human interfaces with airplane systems and the effect of these interfaces on airplane safety and to identify problems related to pilot/airplane interfaces, training/flight crew qualification, operational problems, and recommend changes.

The human factors team identified issues that show vulnerabilities in flight crew management of automation and situation awareness. Issues associated with flight crew management of automation include concerns about:

- Pilot understanding of automation's capabilities, limitations, modes, and operating principles and techniques. The HF Team frequently heard about automation "surprises," where the automation behaved in ways the flight crew did not expect. "Why did it do that?" "What is it doing now?" and "What will it do next?" were common questions expressed by flight crews from operational experience.

- Differing pilot decisions about the appropriate automation level to use or whether to turn the automation on or off when they get into unusual or non-normal situations. This may also lead to potential mismatches with the manufacturers' assumptions about how the flight crew will use the automation.

- Flight crew situation awareness includes vulnerabilities in, for example:

  – Automation/mode awareness. The HF team heard a universal message of concern about each of the aircraft in their charter in this area.

  – Flight path awareness, including sufficient terrain awareness (sometimes involving loss of control or controlled flight into terrain) and energy awareness (especially low energy state).

Recommendations were developed. The HF team acknowledged that implementation of recommendations would not be easy. While implementing, the team believes it is important to adhere to the following principles:

- Minimize human error. It is impossible to prevent all human error without removing the human flexibility and adaptability that contributes significantly to safety. Moreover, it is the negative consequences of error that we wish to eliminate, not necessarily the errors themselves. However, it is still desirable to minimize errors that are design or system induced.

- Increase error tolerance. The systems should be designed to aid the flight crew to detect errors when they occur. Also, the systems should be designed such that errors that do occur have bounds on the undesirable consequences of that result.

- Avoid excess complexity as perceived by the user. The systems should be designed to support the flight crew and should not be perceived as unnecessarily complex.

- Increase system observability, especially by improving system feedback.

- Evaluate new technology or operational changes introduced into the aviation system, especially into the flight deck, for their effect on human performance.

- Invest in human expertise. This investment should include flight crews, designers, regulators, and researchers. We want to reinforce and strengthen the human contribution to safety in a proactive, rather than reactive, way.

The HF team identified barriers to implementation of recommendations. Those included here were considered relevant to the present study and fell under the general category of Misunderstandings About Human Factors described below. *{Annotations in brackets and italics are comments as to how the given point may relate to In-Flight Advisor design.}*

a. **There is a single, agreed upon definition of human factors.** The HF team found that it was difficult to find a commonly agreed upon definition. *{Much of the work in the In-Flight Advisor project involves development of hardware and software for advising or supporting pilot decisions. The pilots' decision-making processes need to be well understood. Because the Advisor under development here is to be used in general aviation, assumed to be at a level lower than corporate aviation, initial training that is typical of military and air carrier pilots will likely not apply. The different level of proficiency should be accounted for in the design. The words "Keep it Simple" take on additional meaning in this context.}*

b. **We don't need to fix the design—just train the pilots more.** Training should not be used as the solution for inadequate design; although sometimes the only short-term approach to dealing with design problems is through training. However, long-term solutions for improved design should also be pursued. *{Along the same lines as above, we have less opportunity for follow-on training, less frequent proficiency training, and less opportunity for remedial training. More investment must be spent up front in the design phase. If the design is faulty, there will be less opportunity to train the pilots. Most general aviation pilots pay for their own training, and the use of the In-Flight Advisor is voluntary. Without proper design, the system could just become an expensive non-used system.}*

c. **Current experience is always applicable to new technology.** While sometimes true, it is risky to assume that new technology will have the same influence on human performance as current experience with the current technology.

d. **HF evaluation is a democratic process**. Just because more than half of a number of evaluators (or test subjects) have a certain opinion or judgment does not necessarily make that judgment the "right" answer from a human performance perspective. *{The designer or a small group of designers do not necessarily represent the user population. The designer may be a potential single user and as such provides a single data point. Quantitative analytical models of human performance in complex systems do not presently exist. Consequently, controlled, statistically valid experiments may be necessary to move HF evaluation beyond "opinion" or the democratic process. Beyond the prototyping stage, potential operational users should be represented.}*

6.5 HUMAN FACTORS DESIGN PROCESS.

6.5.1 Human Factors Design References.

There are many handbooks, design manuals, and textbooks available to aid in design of the aviation interface. Recommendations and guidelines in most of these sources have been developed from empirical experience, experimentation, and even trial and error over the years. Aviation human factors had its roots in World War II, when scientists and the military observed that many aircraft accidents were the result of poorly designed and located switches, controls, and instrument displays [Fitts, 1947 [29]].

Research has continued since World War II. Recent handbooks, checklists, and other references provide excellent guidance on use of color in displays, fonts, design of instruments, population stereotypes in movement of controls, and other design considerations. The following two FAA references are a sample of resources that will be used in the design of the GA In-Flight Advisor:

- *FAA Aircraft Certification Human Factors and Operations Checklist for Standalone GPS Receivers* (FAA, 1995 [30]). This checklist is designed for use in the evaluation of the pilot-system interface characteristics of GPS receivers to be certified according to TSO C129 A1, RTCA/DO-208, and Advisory Circular 20-138. Controls, displays, and operating characteristics are the main focus of this checklist. Appendices include applicable FAA Advisory Circulars, SAE Standards, and MILITARY STANDARD 1472D - *Human Engineering Design Criteria for Military Systems, Equipment, and Facilities.*

- *DOT/FAA/CT-96/1: Human Factors Design Guide For Acquisition of Commercial Off-The-Shelf Subsystems, Non-Developmental Items, and Developmental Systems (HFDG)* (FAA, 1996 [31]). The HFDG provides reference information to assist in the selection, analysis, design, development, and evaluation of new and modified FAA systems and equipment.

6.5.2 Interface Design.

The following discussion on general interface design is modified from Wickens, 1998 [32]. In designing the interface, specialists rely on experience as well as a variety of published standards, principles, and guidelines. According to Nielson, 1993 [33], standards specify how the interface should appear to users where guidelines give advice about usability characteristics. Extensive collections of general user interface guidelines include Brown, 1988 [34], Dumas, 1988 [35], Mayhew, 1992 [36], and [Smith and Mosier, 1986 [37]]. Other authors, such as Norman, 1992 [38] and Nielson, 1993 [33], provide more general principles that designers must apply by analyzing the particular user-product interaction of the given situation.

Four principles offered by Norman are appropriate for any product or system for which ease of use is a prime consideration. Norman, 1992 [38] proposes that products can be made easy to use by increasing the user's conceptual model of how they work and especially what we have to do to interact with them. This is done by applying the following four principles.

a. *Provide a good conceptual model.* If the product somehow conveys to us the basic structure and function of the system, we can imagine interacting with the product in our head. This means we have a good mental model and can correctly predict the results of our actions. As an example, if a person has a good, or at least adequate, conceptual model of their mountain bike, they will be able to imagine what would happen if they moved the right shift lever in a counterclockwise manner. Systems that do not convey an accurate conceptual model or do not convey any model tend to be more difficult to use. An interesting example is that of a standard household thermostat, which does not give users an accurate conceptual model of the household heating system. This is evidenced by the fact that when first turning up the heat in their house, many users turn the

thermostat up too high in the belief that this will somehow make the temperature rise faster than it would otherwise.

b. *Make things visible.* Systems that have many functions and associated controls that are hidden tend to be difficult to use. An example provided by Norman, 1992 [38] is the modern-day telephone. Many phones have special features such as call forwarding. However, it is not clear from the controls (alphanumeric push buttons) and displays (auditory beeps or buzzes) how to make use of these features. The structure, functions, and how to accomplish goals are all hidden.

c. *Use natural mappings.* To make things easy to use, designers should make use of natural mappings. Mapping refers to the relationship between input to or output from a system and the associated system state or event. For example, consider actions to control systems. To move an object up, it seems natural to push a control lever in the same direction. To turn the car to the right, we turn the steering wheel to the right, and to put the car window up, we press the lever up. These are natural mappings or correspondence between two variables.

d. *Provide feedback.* Feedback is also important for ease of use. A product or system should be designed so that users know what action has been actually done and what the results have been within the system. Some systems, such as computers, may have less than adequate feedback. An example can be seen in older software systems where user input resulted in lag time in computer processing. The user did not know whether the input was received by the computer and so performed the action again. Designers finally realized that providing a signal, such as an hourglass, would provide users with feedback that their input had been received.

Even with relatively specific guidelines, it can be difficult to design a product that is easy to use, and the more complex the product, the more difficult the design becomes. Norman, 1992 [38] suggests that to keep a system easy to use, in general, a designer should match the number of controls to the number of functions and organize the control/display panels according to function. Finally, controls or displays not needed for the current task can be hidden to reduce the appearance of system complexity if that is a design goal.

6.5.3 Prototypes.

To support interface design, usability testing, and other human factors activities, product mock-ups and prototypes are built very early in the design process. Prototypes frequently have more of the look and feel of the final product but do not yet have full functionality. The use of prototypes during the design process has a number of advantages including:

- Support of the design team in making ideas concrete
- Support of the design team by providing a communication medium
- Support for heuristic evaluation
- Support for usability testing by giving users something to react to and use

In designing computer interfaces, specialists often use rapid prototyping tools that allow extremely quick changes in the interface so that many design iterations can be performed in a short period of time. Bailey, 1993 [39] studied the effectiveness of prototyping and iterative usability testing. He demonstrated that user performance improved 12 percent with each design iteration and that the average time to perform software-based tasks decreased 35 percent from the first to the final design iteration. Prototypes may potentially be used for any of the evaluations listed below.

6.5.4 Heuristic Evaluation.

A heuristic evaluation of the design(s) means analytically considering the characteristics of a product or system design to determine whether they meet human factors criteria [Desurvire & Thomas, 1993 [40]]. For usability engineering, heuristic evaluation means examining every aspect of the interface to make sure that it meets usability standards [Nielson, 1993 [33]; Nielson & Molich, 1990 [41]] as well as human factors guidelines and criteria. Heuristic evaluations are usually performed by comparing the system interface with the human factors criteria listed in the requirements specification and also with other human factors standards and guidelines. For simple products/systems, checklists may be used for this purpose. At least three evaluators should inspect the product design or prototype in isolation from the others. After each has finished the evaluation, they should be encouraged to communicate and aggregate their findings.

6.5.5 Additional Evaluative Studies and Analyses.

After the design (or set of alternative designs) has received a preliminary review for human factors design flaws, the human factors specialist may perform several other types of analysis. This will depend on the complexity of the system, whether the tasks to be performed are difficult or performed under high workload conditions, and whether there are safety issues associated with the product/system. Analyses that may be performed at this point include:

- Cost/benefit analysis for design alternatives
- Trade-off analyses or studies (e.g., which display works best)
- Workload analysis
- Safety, human reliability, or hazard analyses

  - *Cost/Benefit Analysis for Design Alternatives.* Cost/benefit analysis refers to the comparison of different design features and their implications. The cost can be defined monetarily or in other ways. For example, product weight might be greater for one design than another. The most common method for doing a quantitative cost/benefit analysis is to do a decision matrix. The features, or variables, on which the design alternative differ are listed on the left side of a matrix. Examples might be weight, manufacturing cost, range of users who would have access to the product, and so on. Each feature is given a weight representing how important the feature is in the overall picture. Then, each design alternative is assigned a number representing where it stands with respect to the feature. Finally, each design alternative is given a total score by

multiplying individual scores by the feature weights and then adding the scores together.

- *Trade-Off Analyses.* Sometimes a design feature, such as a particular display, can be implemented in more than one way. The human factors analyst might not have data or guidelines to direct a decision between alternatives. Many times a small-scale study is conducted to determine which design alternative results in the best performance (e.g., fastest or most accurate). These studies are referred to as trade studies. Sometimes the analysis can be done by the designer without actually running studies, using methods such as modeling, or using performance estimates. If multiple factors are considered, the design tradeoffs might revolve around the design with the greatest number of advantages and the smallest number of disadvantages.

- *Workload Analysis.* The product or system being designed may be complex enough to evaluate whether it is going to place excessive mental workloads on the user, either alone or performed in conjunction with other tasks. When this is the case, the human factors specialist performs an analysis to predict the workloads that will be placed on the user during various points of task performance.

- *Safety Analysis.* Any time a product or system has implications for human safety, analyses should be conducted to identify potential hazards or the likelihood of human error. There are several standard methods for performing such analyses, such as Failure Modes and Effects Analysis or Human Reliability Analysis. Designers must assess hazards associated with the product during all stages of the system life cycle.

6.5.6 Thirteen Principles of Display Design.

Specific selection of components in a display design depends upon the task that the operator is expected to perform. Displays should be designed or selected so that they are optimally suited for the required task. The interface of a human operator with a complex system provides the means by which the operator communicates with the system and vice versa. Different methods of user input to the system may be selected, depending on the task that the user is required to accomplish. The system interprets the user input, and a change in state takes place. If the user input was correct, and the system interpretation and resulting system actions are correct, then the user should be able to sense the new system state through the system information displays. For example, entering waypoints into an automated navigation system sometimes results in data entry error. The error may not be detected by the system. As a result, the pilot may not detect the error until the automated navigation system begins to fly to the improper waypoint. The necessary information should be presented on a display and formatted in a way that will support perception and understanding. A detailed information analysis will identify what the operator needs to know to carry out the task [Wickens, 1998 [32]].

The following thirteen principles of display design are presented by Wickens, 1998 [32]. These principles are grounded in the strengths and weaknesses of human perception and performance,

and it is through the careful application of these principles to the output of the information analysis that the best displays will emerge. The thirteen principles are:

a. *Avoid absolute judgment:* Operators should not be required to judge the level of a variable on the basis of a single sensory variable, like color, size, or loudness, which contains more than five to seven possible levels.

b. *Top-down processing:* People will perceive and interpret signals on the basis of their past experience. If a signal is to be contrary to the operators expectation, more physical evidence must be provided to guarantee that it will be interpreted correctly.

c. *Redundancy gain:* A message that is presented in more than one form will be more likely to be correctly interpreted. The gain is most likely if alternative physical forms, such as voice and print or shape and color, are used to transmit the message.

d. *Discriminability - similarity causes confusion:* Similar appearing signals are likely to be confused.

e. *Principle of pictorial realism:* A display should look like the variable that it represents or should be configured in the way that the operator conceptualizes the environment.

f. *Principle of the moving part:* The moving elements of any display of dynamic information should move in a spatial pattern and direction that is compatible with the user's mental model of how the represented element moves.

g. *Ecological interface design:* Displays that have a close correspondence to the environment being displayed. This is a relatively new area of human factors research but one that has great intuitive appeal for improvement of interface designs of complex dynamic systems.

h. *Minimizing information access costs:* Minimize net costs of obtaining information by keeping frequently accessed sources in a location such that the cost of travelling between them is small.

i. *Proximity compatibility principle:* Sometimes two or more sources of information are related to the same task and must be mentally integrated to complete the task. Information sources can be linked by color or displays integrated in close physical proximity. However, sometimes proximity can be too close, resulting in clutter.

j. *Principle of multiple resources:* Processing a lot of information can be facilitated by dividing it across resources such as presenting visual and auditory information concurrently.

k. *Principle of predictive aiding:* A display that can explicitly predict what will happen will generally enhance human performance. Predicting the future is a complex cognitive task for which humans are not well suited.

l. *Principle of knowledge in the world:* Place specific reminders in the task environment to cue the operator as to when and what needs to be accomplished. A pilot's checklist is an example. On the other hand, knowledge in the head, which requires memorization, often degrades performance.

m. *Principle of consistency:* Design displays that are consistent with other displays the user may be using. Exploit old habits from the old displays that will transfer to the new displays.

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APPENDIX A—LITERATURE SURVEY WITH ABSTRACTS

TABLE OF CONTENTS

OTHER LITERATURE REVIEWS

Martin, W. L. (1986), "An Assessment of Artificial Intelligence and Expert Systems Technology for Application to Management of Cockpit Systems," Technical Report AAMRL-TR-86-040.

DECISION AIDING ARCHITECTURES

AVIATION.

Ballard, D. and Rippy, L., "A Knowledge-Based Decision Aid for Enhanced Situational Awareness," *Proceedings of the 13th AIAA/IEEE Digital Avionics Systems Conference*, pp. 340-7, 1994. *See also* http://www.reticular.com/Library/SA/sa_index.html.

This paper describes a multiyear research and development effort to develop a system for performing situation assessments in next-generation Army helicopters. A formal definition of situation assessment is provided and describes the motivation for the architecture based on studies in human cognition and attention. The paper describes the overall architecture and the processing paradigm used in performing situation assessment. In particular, it is shown how extensive knowledge about the battlefield, the threat, terrain, enemy, and friendly doctrine can be used to aid in performing situation assessment. Also shown is how the overall inferencing process can be controlled in such a way as to bound the requirements for scarce computational resources. A system composed of three independent reasoning subsystems performing recognition, evaluation, and prediction is described. Also described are the knowledge bases and important data structures used in developing the system.

Bittermann, V., Deker, G., Sassus, P., Mielnik, J. C., and Jud, J. M., "FINDER, A System Providing Complex Decision-Support for Commercial Transport Replanning Operations," *IEEE Aerospace and Electronic Systems Magazine*, 9(3), 12-18, 1994.

Decision-aid systems, likely to appear in future aircraft generations, could play a central role in the cockpit thanks to the broad spectrum of functionalities and decision support facilities they will offer to the crew. As part of such systems, the exploratory FINDER* mock-up is a knowledge-based system (KBS) designed to help crew members continually optimize their flight plan by suggesting solutions considering exhaustive information related to flight context, either on pilot request or upon external information occurrence. The successful evaluation by AIR FRANCE pilots of that first mock-up dedicated to diversion procedure on pilot request has led to the current development of an enhanced system with nominal en route operations and real-time capabilities. Nominal en route operations concern the optimization with respect to an evolutive constraining or favouring environment (due to weather, traffic or regulated areas, and Extended-Range Twin-Engine Operations (ETOPS) constraints). This study paves the way for a future Flight Assistant System concept which is already under investigation and may take place in SEXTANT Avionique's future development steps.

Funk, K., Woo Chang Cha, Wilson, R., Zaspel, J., and Braune, R., "Development and Evaluation of an Aid to Facilitate Agenda Management, in *Proceedings of the 1997 IEEE International Conference on Systems, Man, and Cybernetics*, Vol. 4, pp. 3120-5, 1997.

Commercial air transportation has an admirable safety record; yet each year hundreds of lives and hundreds of millions of dollars worth of property are lost in air crashes in the United States alone. About two-thirds of these aircraft accidents are caused, in part, by pilot error. Many of these errors are errors in performing flight deck (or cockpit) functions; others are errors in managing flight deck goals and the functions to achieve those goals. The paper describes the development and evaluation of a prototype computational aid to facilitate the management of flight deck goals and functions.

Geddes, N.D., Lee, R.J., and Brown, J.L., "Portable Lightweight Associate for Urban Helicopter Pilotage," *AIAA/IEEE Digital Avionics Systems Conference – Proceedings*, pp. 7.1-11-7.1-18, 1997.

The Urban Helicopter Associate System (UHAS) is an advanced demonstration prototype of an associate system for aiding pilots of rotorcraft engaged in complex missions in urban environments. It is the first of an evolving class of lightweight associate systems that provide full associate decision aiding in a lightweight computing environment. The UHAS is hosted on a laptop computer and is intended for limited flight demonstrations in law enforcement and emergency medical services (EMS) scenarios.

Hammer, J.M. and Small, R.L., "An Intelligent Interface in an Associate System," *Human/Technology Interaction in Complex Systems*, W.B. Rouse, ed., Greenwich, CT, JAI Press, Vol. 7, pp. 1-44, 1995.

The purposes for initiating the Pilot's Associate (PA) program were to exploit an existing technology base for defense purposes and to serve as an application area within the Strategic Computing Program. The PA program was a typical Defense Advanced Research Projects Agency (DARPA) project in that it sought to advance the state of the art in computing technology, decision support, and artificial intelligence (AI). The purpose of the program was to apply AI to aid pilots of single-seat aircraft. As to automation, PA's purpose was to help the pilot perform the mission by presenting information in a readily understood manner and offering aid via the use of knowledge bases. This paper discusses the key technical challenges, the requirements, and the architecture of both the associate system and the intelligent interface. The architecture is discussed in terms of responsibilities, theory, design, and lessons learned. It concludes with overall observations about associate system technology.

Miller, C. A. and Funk, H. B., "Knowledge Requirements for Information Management: A Rotorcraft Pilot's Associate Example," *Human-Automation Interaction: Research and Practice*, M. Mouloua and J. M. Koonce, eds., Mahwah, NJ: Lawrence Erlbaum Associates, pp. 186-192, 1997.

Information Management (IM) involves sifting through a potentially overwhelming quantity of incoming data and presenting only what the human operator(s) currently need in a manner that will be easily understood by them. We claim that the design of any automated IM system requires the representation and use of four types of knowledge:

1. Task or context knowledge.
2. Information requirements knowledge organized by task or context.
3. Information presentation knowledge organized by information requirement.
4. A selection mechanism for choosing among presentation options.

In this paper, we discuss our work on an IM system for the U.S. Army's Rotorcraft Pilot's Associate (RPA) – both in the context of RPA as a whole and with regards to the implementation and usage of the four types of knowledge described above.

Mulgund, S., Rinkus, G., Illgen, C., Zacharius, G., and Friskie, J., "OLIPSA: On-line Intelligent Processor for Situation Assessment," In *Proceedings for the Second Annual Symposium and Exhibition on Situation Awareness in the Tactical Air Environment*, pp. 113-126, 1997.

This paper describes a study that assessed the feasibility of developing a concept prototype for an On-Line Intelligent Processor for Situation Assessment (OLIPSA) to serve as a central processor to manage sensors, drive decision aids, and adapt pilot/vehicle interfaces in the next-generation military cockpit. The approach integrates several enabling technologies to perform the three essential functions of real-time situation assessment:

- Event detection using a fuzzy logic processor and an event rulebase to transform fused sensor data into situationally relevant semantic variables.

- Current situation assessment is performed using a belief network model to combine detected events into a holistic picture of the current situation for probabilistic reasoning in the presence of uncertainty.

- Future situation prediction is carried out via case-based reasoning to project the current situation into the future via experience-based outcome prediction.

Onken, R., "The Cockpit Assistant System CASSY as an On-Board Player in the ATM Environment," paper presented at the *1st USA/Europe Air Traffic Management Research and Development Seminar*, 1997. *See also* http://atm-seminar-97.eurocontrol.fr/onken.htm.

This paper presents a concept which warrants a highest possible degree of situation awareness and efficient man-machine interaction on the flight deck, not being confined to the cockpit domain though. This concept offers the solution to counteract the possible negative consequences of certain flight situations, which are usually not known in advance and are susceptible to pilot errors. It is founded on significant advances in cognitive system engineering in order to accomplish and really warrant complementary deployment of automation technology at the pilot's working station in favor of flight safety and mission effectiveness. These

technologies enable a cockpit automation in order to systematically comply with the requirements of Human-Centered Automation (HCA). They also allow to quantify at which degree these requirements are met. The underlying approach behind the concept will be illustrated in this paper by the functional concept and development of the cockpit assistant system (CASSY). It has been extensively tested in flight simulators and has been successfully field tested with the Advanced Technologies Test Aircraft System (ATTAS) of the German Center for Aeronautics and Space Flight (DLR). Some of the results of these flight trials will also be presented in this paper.

This demonstrates that the time has come where interaction between the human team and cockpit information systems no longer have to be designed on a vague basis of specifications. The advances in technology provide the necessary basis to systematically reflect requirements for human-centered automation into clear-cut specifications and system design. Therefore, this paper also presents recommendations for how to proceed in order to amend working positions of humans in air traffic management (ATM), including air traffic service providers and airline operation centers.

Robson, M., Fairbanks, M., and Shorthose, M., "Final Report on a Feasibility Study Into Intelligent Flight Path Monitor," Civil Aviation Authority contract 7D/S/1240, 1995.

A cause of accidents attributable to pilot error is lack of crew situational awareness. A more recent phenomena, in which crews lack awareness of what the aircraft's automated systems are doing, could be tackled in several ways including increasing the intelligence of the aircraft systems so as to provide crews with a smooth workload under all situations and prioritize crew tasking. Intelligent Flight Path Monitoring (IFPM) is an artificially intelligent agent to help in these situations by performing situation assessment and drawing crew attention to the most relevant information. CASSY is such a prototype system that has been tested in simulators and experimental aircraft. This report investigates a functional design (and the requirements for) an IFPM and two particular architectures: one for an IFPM suitable for retrofit to existing aircraft and for future aircraft using advanced technologies. Much can be achieved with a design that uses existing technologies. However, a fully functional version of the design requires new technology such as air traffic control (ATC) datalink and voice recognition capability. Sophisticated warning functions can be provided without placing any higher specifications on other aircraft systems. The main risk involved in production of an IFPM would be in the safety certification of the AI system components that might be required.

Rodin, E. Y., "Artificial Intelligence Methods in Pursuit of Evasion Differential Games," Final Report under contract AFOSR-87-0252, 1990.

Roorda, J. and Crowe, M., "Artificial Neural Systems Application to the Simulation of Air Combat Decision-Making," final report under contract F33615-88-C-0066, 1992.

Rouse, W. B., Geddes, N. D., and Curry, R. E., "Architecture for Intelligent Interfaces: Outline of an Approach to Supporting Operators of Complex Systems," *Human-Computer Interaction*, 3(2), pp. 87-122, 1987.

The conceptual design of a comprehensive support system for operators of complex systems is presented. Key functions within the support system architecture include information management, error monitoring, and adaptive aiding. One of the central knowledge sources underlying this functionality is an operator model that involves a combination of algorithmic and symbolic models for assessing and predicting an operator's activities, awareness, intentions, resources, and performance. Functional block diagrams are presented for the overall architecture as well as the key elements within this architecture. A variety of difficult design issues are discussed, and ongoing efforts aimed at resolving these issues are noted.

Sherry, L., Kelley, H. J., McCrobie, D., and Polson, P., "A Framework for the Design of Intentional Systems in Support of Cooperative Human-Machine Systems," in *Proceedings of the 9th International Symposium on Aviation Psychology*, pp. 280-286, 1997.

Wierner, E., 1989, Human Factors of Advanced Technology ('glass cockpit') Transport Aircraft" NASA contractor report No. 177528, NASA AMES Research Center.

Wiener summarizes the information required by the flight crew to fully comprehend the behavior of the avionics as answers to the questions: What is it doing now? Why is it doing that? What is it going to do next? The research described in this paper proposes to specify the behavior of the avionics in a manner that directly answers these questions. The communication between flight crew and avionics is based on a framework of cooperation between the cockpit agents, where the agents behavior is defined by intentions associated with situation/action pairs. This method is demonstrated by the specification of the automation proposed for the Vertical Guidance function of the High-Speed Civil Transport. Design of the Flight Mode Annunciation to communicate the intentions of the avionics and the interactive computer-based training that exploits the intentional formal model of the avionics are discussed.

Smith, P.J., McCoy, C.E., and Layton, C., "Brittleness in the Design of Cooperative Problem-Solving Systems: The Effects On User Performance," *IEEE Transactions on Systems, Man, and Cybernetics*, 27(3), pp. 360-371, 1997.

One of the critical problems in the design and use of advanced decision/support systems is their potential brittleness. This brittleness can arise because of the inability of the designer to anticipate and design for all of the scenarios that could arise during the use of the system, a deliberate decision by the designer to use an oversimplified model of the decision task (due to cost, time, or technological limitations), a failure of the designer to correctly anticipate the behavior of the system in certain situations, or a failure to correctly implement the intended design. The typical safety valve to deal with this problem is to keep a person in the loop, requiring that person to apply his or her expertise in making the final decision on what actions to take. This paper provides empirical data on how the role of the decision support system can have a major impact on the effectiveness of this design strategy. Using flight planning for commercial airlines as a testbed, three alternative designs for a graphical flight planning tool were evaluated using 27 dispatchers and 30 pilots as subjects. The results show that the presentation of a suggestion or recommendation by the computer early in the person's own problem evaluation can have a significant impact on that person's decision processes, influencing situation assessment,

and the evaluation of alternative solutions. If the scenario is one where the computer's brittleness leads to a poor recommendation, this impact can strongly influence the person to make a poor decision.

Stiles, P., Bodenhorn, C., and Baker B., "Decision Aiding on Rotorcraft Pilot's Associate," *Annual Forum Proceedings-American Helicopter Society 1998*; 54(2), pp. 1212-1224, 1998.

In the future, data will be flooding into the cockpit from onboard sensors, offboard over-the-horizon and intelligence collection systems, and directly from friendly air and ground elements. Without onboard systems to help the crew analyze and use all the data, it will be overwhelming. Aircrews will not be able to effectively understand what they face on the battlefield: who's out there, what issues require immediate attention, whether or not their current mission plan has been compromised, and what new plan would provide maximum advantage and minimum risk. However, with the right kind of decision aiding support, this data can dramatically improve survivability, lethality, and operational tempo. The Rotorcraft Pilot's Associate (RPA) team has made significant progress in information management and decision aiding technology. This paper focuses on three aspects of RPA:

1. Improved situation awareness provided by Data Fusion and Battlefield Assessment.
2. High-level mission replanning response controlled by the hierarchical Mission Planner.
3. Determination of optimal combat battle positions by the Attack Planner.

Strohal, M., Onken, R., Salvendy, G., Smith, M.J., and Koubek, R.J., "The Crew Assistant Military Aircraft (CAMA)," *Proceedings of the Seventh International Conference on Human-Computer Interaction (HCI International '97)*, Vol. 2, pp. 7-10, 1997.

The paper describes the concept of the knowledge-based Cockpit Assistant Military Aircraft (CAMA) and its functions as an example of human centered automation. A general survey of CAMA with its structure, functions, and interfaces are given with a brief description of the individual system modules.

Stutz, P., Onken, R., Salvendy, G., Smith, M.J., and Koubek, R.J., "Adaptive Pilot Modeling Within Cockpit Crew Assistance," in *Proceedings of the Seventh International Conference on Human-Computer Interaction (HCI International '97)*, Vol. 1, pp. 733-6, 1997.

Cockpit Assistant Systems are being developed in support of human-centered automation on aircraft flight decks. A short introduction into the principles of Cockpit Crew Assistance is given, followed by a more detailed description of the adaptive behaviour model to be used in that kind of system. Monitoring of crew behaviour is a vital part of the system's situation assessment process. This can be accomplished by comparison between expected and actual pilot actions. It will be shown how the system's normative behavioural model, based on pilot handbooks and air traffic regulations, is further enhanced by learning components providing adaptation to the individual pilot by use of a combination of Petri nets and case-based reasoning (CBR).

Toms, M. L., Cavallaro, J. J., Cone, S. M., Moore, F. W., and Gonzalez-Garcia, A., "Considerations for Implementing an Instrument Approach Aid," paper presented at the *Fourth International Workshop on Human-Computer Teamwork*, Sept. 23-26, 1997.

Woo Chang Cha Funk, K., "Recognizing Pilot Goals to Facilitate Agenda Management," in *Proceedings of the 9th International Symposium on Aviation Psychology*, pp. 268-272, 1997.

In modern aircraft, the human pilots are no longer the only actors that control the aircraft and its systems. Machine actors, such as the autopilot and flight management system, also play an active role in control. In fact, several recent accidents occurred due to goal conflicts between human and machine actors. To prevent the occurrence of these and other activity management problems, a computational aid called the Agenda Manager (AMgr) is being developed. The AMgr, which operates in a part-task simulator environment, attempts to facilitate the management of goals the actors are trying to accomplish and the functions being performed to accomplish them. To provide accurate knowledge of pilot goals for AMgr, a Goal Communication Method (GCM) was developed. The embedded GCM recognizes explicit and/or implicit pilot goals and declares them to the AMgr. This paper presents the development, architecture, operation, and evaluation of GCM.

NON-PILOT.

Boy, G.A., "Operator Assistant Systems," *International Journal of Man-Machine Studies, 27*, pp. 541-554, 1987.

This paper presents a knowledge-based system (KBS) methodology to study human-machine interactions and levels of autonomy in allocation of process control tasks with a view to designing operational systems. The author focuses on a situational/analytical representation and a method for eliciting operator logic to refine a KBS shell called an operator assistant (OA). For the OA to be an efficient online aid, it is necessary to know what level of autonomy gives the optimal performance of the overall man-machine system. OA structure has been used to design a working KBS called HORSES (human-orbital refueling system-expert system). Protocol analysis of pilots interacting with this system has revealed that the a priori analytical knowledge becomes more structured with training and the situation patterns more complex and dynamic. This approach can improve our understanding of human and automatic reasoning and their most efficient interactions.

Hutchins, S. G., "Principles for Intelligent Decision Aiding," NRAD TR 1718, Naval Command, Control and Ocean Surveillance Center, San Diego, CA, RDT and E Div., 1996.

The Tactical Decision-Making Under Stress (TADMUS) program is being conducted to apply recent developments in cognitive theory and human-system interaction technology to the design of a decision support system (DSS) for enhancing tactical decision-making under the highly complex conditions involved in littoral settings or any short-fused, dynamic decision-making situation. Our goal is to present decision support information in a format that (1) minimizes any mismatches between the cognitive characteristics of the human decision-maker and the design

and response characteristics of the decision support system, (2) mitigates the shortcomings of current tactical displays that impose high information processing demands and exceed the limitations of human memory, and (3) synthesizes numeric data into graphic representations to facilitate the interpretation of spatial data.

Jones, P. M. and Mitchell, C. M., "Human-Computer Cooperative Problem Solving: Theory, Design, and Evaluation of an Intelligent Associate System," *IEEE Transactions On Systems, Man, and Cybernetics*, 25(7), pp. 1039-1053, 1995.

One approach to aiding the human supervisory controller of a complex dynamic system is to provide an intelligent operator's associate. Jones et al. propose a prescriptive theory of human-computer cooperative problem solving and describe the design and evaluation of a prototype system based on the theory. The theory consists of five principles: human-in-charge, mutual intelligibility, openness and honesty, management of trouble, and multiple perspectives. A prototype intelligent associate system, the Georgia Tech Mission Operations Cooperative Assistant (GT-MOCA), is the embodiment of these principles that provide a collection of context-sensitive resources for the human operator of a simulated satellite ground control system. These resources include an interactive visualization of current activities, an organized message list of important events, and interactive graphics depicting the current state of the controlled system. An evaluation study utilizing actual NASA satellite ground controllers showed that GT-MOCA was perceived as useful and provided performance benefits for certain portions of the control task.

Judson, B., "A Tanker Navigation Safety System," *Journal of Navigation,* 50(1), pp. 97-108, 1997.

This paper summarizes the results of Phase 3 of the Arctic Tanker Risk Analysis Project (ATRA) which provided a prototype Tanker Navigation Safety System (TNSS). TNSS is a shipboard risk management system capable of route planning and decision support based upon a knowledge data base. The objective of the project was to provide timely risk assessment information to a mariner or decision-maker in a system capable of integration with existing Electronic Chart Display and Information Systems (ECDIS) or shipboard PC systems. The historical information was to include: accident location, frequency and type, ice, wind, visibility, environmental sensitivity, and other factors. The specifications of the TNSS prototype were expanded so that risk could be assessed for each track in a route plan by applying a predictive accident model patterned after the navigation and collision avoidance process.

Krishnan, R., "On Integrating Artificial Intelligence and Decision Analysis Technologies: Determining Support Requirements for a Combat Force," final report under contract DAAH04-94-G-0239, 1998. *See also* http://www.heinz.cmu.edu/project/dnet.

Larsson, J.E. and Hayes-Roth, B., "Guardian: An Intelligent Autonomous Agent for Medical Monitoring and Diagnosis," *IEEE Expert*, 13(1), pp. 58-64, 1998.

Guardian is a knowledge-based system designed to perform medical monitoring and diagnosis for post-cardiac surgery patients. The system is an autonomous agent with a flexible architecture in which several algorithms cooperate to produce diagnoses and treatment plans under real-time conditions. Guardian has undergone several tests, and with the help of a patient-simulator system, its performance is compared to that of a human physician. The test results indicate that such a system is valuable, both in increasing the effectiveness of treatments and decreasing the cost of health care.

Larsson, J. E., Hayes-Roth, B., and Gaba, D. M., "Goals and Functions of the Human Body: An MFM Model for Fault Diagnosis," *IEEE Transactions on Systems, Man, and Cybernetics*, 27(6), pp. 758-765, 1997.

This correspondence describes the use of explicit models of goals and functions for monitoring and diagnosis of intensive-care patients. The method is based on multilevel flow models (MFM) and used in the Guardian system. It provides this system with alarm analysis, fault diagnosis, and automatic generation of explanations. Advantages include a relatively easy knowledge engineering effort and good properties for use in a system with hard real-time deadlines. The results of some experiments are also reported.

ALERTING/MONITORING AUTOMATION

AVIATION.

Billings, C. E., "Aviation Automation: The Search for a Human-Centered Approach," Mahwah, NJ, Lawrence Erlbaum Associates, 1997.

Ernst-Fortin, S. T., Small, R. L., Bass, E. J., and Hogans, Jr., J., "An Adaptive Cockpit Hazard Monitoring System," final report under US Air Force contract #F33615-95-C-3611, Norcross, GA, Search Technology, Inc., 1997.

The Phase II research had several goals. One was to focus on improving and implementing the enhanced Hazard Monitor (HM) design, especially arbitration, designed in Phase I. Another was to tailor the Phase I knowledge base for the new advanced version of the Lockheed C-130 cargo plane. To allow for demonstration with a pilot interface, HM was integrated with two different airplane simulators. A final goal was to analyze both the military and civilian avionics markets to the extent needed to make a commercialization decision; that is, to decide upon a Phase III strategy. Phase II improved and expanded upon the following results from Phase I. For a specific cockpit environment, Search Technology conducted numerous knowledge engineering sessions with industry experts to conceptually tailor its HM prototype and the domain knowledge embodied as Expectation Networks. A broad taxonomy of hazard situations encountered by military flight crews was compiled to understand what HM might theoretically have to monitor. Phase I included the conceptual design of the arbitration of potentially conflicting hazard avoidance steps resulting from the simultaneous use of multiple procedure checklists (and their corresponding Expectation Networks). Arbitration and the set of Expectation Networks were tested against a scenario of events designed to demonstrate HM's utility. Results from both

phases indicated that HM is a technically feasible and attractive approach to helping aircrews avoid the negative consequences of hazardous flight situations. Discussions with experts in various aviation applications—airborne, ground-based control and training—provide motivation for the commercialization effort that is the goal of Phase III.

Funk, K. H. and Braune, R., "Expanding the Functionality of Existing Airframe Systems Monitors: The Agenda Manager," in *Proceedings of the 9th International Symposium on Aviation Psychology*, pp. 887-892, 1997.

Although the existing centralized indication and alerting systems have generally been very well received by the operational community, they are limited in at least the following areas:

1. Ordering and prioritization of information within an alert category (now it is chronological).

2. Anticipation of flight crew intent on a moment-by-moment logic.

3. Merging information from multiple failures.

This paper discusses an experimental function-oriented monitoring, alerting, and warning system called the Agenda Manager. It monitors system status and alerts and warns the pilot to nominal abnormalities. It also monitors systems with respect to pilot goals and assesses whether these goals are being accomplished satisfactorily.

Greenberg, A. D., Small, R. L., Zenyuh, J. P., and Skidmore, M. D., "Monitoring for Hazard in Flight Management Systems," *European Journal of Operational Research*, 84, Amsterdam, Netherlands, Elsevier Science, B. V., 1995.

This paper discusses the theoretical basis and practical architecture for a real-time hazard monitor, historically termed an error monitor (EM). EM uses an expectation-based theory of action interpretation. Two knowledge acquisition techniques, interaction analysis and situation analysis, capture domain knowledge. Expectation networks (ENets) are the knowledge structures which reflect these analyses. The level of remediation of error is directly related to the level of risk. The paper presents test results using EM in conjunction with a flight management system (FMS) emulator.

Hansman, R. J., Wanke, C., Kuchar, J., Mykityshyn, M., Hahn, E., and Midkiff, A., "Hazard Alerting and Situational Awareness in Advanced Air Transport Cockpits," ICAS-92-3.9.4, 18th ICAS Congress, Beijing, China, September 1992.

Advances in avionics and display technology have significantly changed the cockpit environment in current glass-cockpit aircraft. Recent developments in display technology, on-board processing, data storage, and datalinked communications are likely to further alter the environment in second and third generation glass-cockpit aircraft. The interaction of advanced cockpit technology with human cognitive performance has been a major area of activity within

the Massachusetts Institute of Technology (MIT) Aeronautical Systems Laboratory. This paper presents an overview of the MIT Advanced Cockpit Simulation Facility. Several recent research projects are briefly reviewed and the most important results are summarized.

Kuchar, J. K., "Methodology for Alerting-System Performance Evaluation, *AIAA Journal of Guidance, Control, and Dynamics*, 19(2), March-April 1996.

A probabilistic-analysis methodology is described that provides quantitative measures of alerting-system performance, including the probabilities of a false alarm and missed detection. As part of the approach, the alerting decision is recast as a signal-detection problem, and system operating-characteristic curves are introduced to describe the tradeoffs between alerting-threshold placement and system performance. The methodology fills the need for a means to determine appropriate alerting thresholds and to quantify the potential benefits that are possible through changes in the design of the system. Because the methodology is developed in a generalized manner, it can be used in a variety of vehicle, transportation system, and process-control applications. The methodology is demonstrated through an example application to the Traffic Alert and Collision Avoidance System (TCAS). Recent changes in TCAS alerting thresholds are shown to reduce the probability of a false alarm in situations known to produce frequent nuisance alerts in actual operations.

Kuchar, J. K. and Hansman, R. J., "A Unified Methodology for the Evaluation of Hazard Alerting Systems," MIT Aeronautical Systems Laboratory Report, ASL-95-1, January 1995.

Randle, R. J., Larsen, W. E., and Williams, D. H., "Some Human Factors Issues in the Development and Evaluation of Cockpit Alerting and Warning Systems," NASA Reference Publication 1055, Moffett Field, CA, NASA Ames Research Center, 1980.

The purpose of this report is to provide system development personnel with a set of general guidelines for evaluating a newly developed cockpit alerting and warning system in terms of human factors issues. Although the discussion centers around a general methodology, it has been made specific to the issues involved in alerting systems.

Satchell, P., "Cockpit Monitoring and Alerting Systems," Brookfield, Ashgate Publishing Company, 1993. *See also* Satchell.htm.

Yang, L. C. and Kuchar, J. K., "Prototype Conflict Alerting Logic for Free Flight," *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 20, No. 4, July-August 1997.

The development of a prototype alerting system for a conceptual free-flight environment is discussed. The alerting logic is based on a probabilistic model of aircraft sensor and trajectory uncertainties that need not be Gaussian distributions. Monte Carlo simulations are used over a range of encounter situations to estimate conflict probability as a function of intruder position, heading, and speed as determined through a datalink between aircraft. Additionally, the probability of conflict along potential avoidance trajectories is used to indicate whether adequate space is available to resolve a conflict. Intruder intent information, e.g., flight plan, is not

included in the model but could be used to reduce the uncertainty in the projected trajectory. Four alert stages are defined based on the probability of conflict and on the avoidance maneuvers that are available to the flight crew. Preliminary results from numerical evaluations and from a piloted simulator study at NASA Ames Research Center are summarized.

NON-PILOT.

Khosla, R. and Dillon, T., "Learning Knowledge and Strategy of a Neuro-Expert System Architecture in Alarm Processing," *IEEE Transactions on Power Systems*, 12(4), pp. 1610-1618, 1997.

In this paper the learning knowledge and strategy of a generic neuro-expert system (GENUES) architecture for training neural networks in an alarm processing system is described. The GENUES architecture forms an important part of an integrated architecture used for developing a real-time alarm processing system in a regional power system control center. The paper also reports on some of the important implementation issues related to alarm processing.

Patecornell, M. E. and Fischbeck, P. S., "Probabilistic-Interpretation of Command and Control Signals—Bayesian Updating of the Probability of Nuclear Attack," *Reliability Engineering and System Safety,* 47(1), pp. 27-36, 1995.

A warning system such as a Command, Control, Communication, and Intelligence system operates on the basis of various sources of information among which are signals from sensors. A fundamental problem in the use of such signals is that these sensors provide only imperfect information. Bayesian probability, defined as a degree of belief in the possibility of each event, is therefore a key concept in the logical treatment of the signals. However, the base of evidence for estimation of these probabilities may be small and, therefore, the results of the updating (posterior probabilities of attack) may also be uncertain. In this paper, the case where uncertainties hinge upon the existence of several possible underlying hypotheses (or models) and where the decision-maker attributes a different probability of attack to each of these fundamental hypothesesis is examined. A two-stage Bayesian updating process is presented: first of the probabilities of the fundamental hypotheses then of the probabilities of attack conditional on each hypothesis given a positive signal from the Command, Control, Communication, and Intelligence system. The method is illustrated in the discrete case where there are only two possible fundamental hypotheses and in the case of a continuous set of hypotheses. The implications of the results for decision-making are also briefly discussed. The method can be generalized to other warning systems with imperfect signals when the prior probability of the event of interest is uncertain.

HUMAN INTENT/PERFORMANCE MODELING

AVIATION.

Amalberti, R. and Deblon, F., "Cognitive Modelling of Fighter Aircraft Process Control: A Step Towards an Intelligent On-Board Assistance System," *International Journal of Man-Machine Studies*, 36(5), pp. 639-71, 1992.

A baseline description of a cognitive model that has been successfully implemented on high-speed, low-altitude navigation fighter plane missions illustrates designs for an intelligent assistance system for future French combat aircraft. The outcomes are based on several empirical studies. Task complexity (risk, uncertainty, time pressure) is extreme and provides a prototypical example of a rapid process control situation which requires specific assistance problems. The article is divided into three sections: a general review discusses implications of the specific requirements for coupling an intelligent assistance system to pilots, an empirical analysis of missions carried out by novice and experienced pilots forms the basis for a cognitive model of in-flight navigation problem solving, and the cognitive model described above serves as the basis for a computer cognitive model for flying high-speed, low-altitude navigation missions; and this computer cognitive model serves to develop an intelligent navigation assistance system which can function as an automaton or as a tactical support system.

Callantine, T. J., Mitchell, C., and Palmer, E., "Tracking Operator Activities in Complex Systems: An Experimental Evaluation Using Boeing 757 Pilots," in *Proceedings of the 9th International Symposium on Aviation Psychology*, pp. 842-847, 1997.

The Georgia Tech Crew Activity Tracking System (GT-CATS) was designed and implemented to predict and interpret the activities of B-757 pilots. This paper describes an experimental evaluation of GT-CATS performed using ten type-rated pilots from a major air carrier as subjects. The results show that, overall, GT-CATS was effective in anticipating and interpreting pilot actions in real time.

Corker, K., Pisanich, G., and Bunzo, M., "A Cognitive System Model For Human/Automation Dynamics in Airspace Management," *1st U.S.A/Europe Air Traffic Management R and D Seminar*, Saclay, France, June 17-20, 1997. *See also* http://atm-seminar-97.eurocontrol.fr/corker.htm.

The world community of aviation operations is engaged in a vast, system-wide experiment in human/system integration. This system evolution profoundly challenges human performance prediction and the cognitive sciences. Engineering systems design requires models of human performance to guide appropriate design, to evaluate the effectiveness of the system, and to assure the safe operation of the system. The performance challenge, that is represented by many concepts of operation, is to link increasingly powerful and accurate data systems, sensors, and optimization systems to humans whose responsibility it is manage and act in the system.

Specifically, increasingly accurate data on physical and temporal position of the assets of the Air Traffic Management (ATM) system are available. These include the aircraft, the crew, the cargo, and the maintenance resources. More powerful and sophisticated aiding systems are being developed. The dual function of these tools is to reduce constraints when possible (providing more autonomy and thus less predictability to aircraft operations) and to provide accurate positive control in four dimensions (requiring increased system gain and constraint) in the terminal area.

Our charter is to develop human performance models that predict the consequences of the interaction between these advanced automation technologies and the human component in the ATM system. These models have two purposes. First, they are to provide guidance for the design of the aiding system to define the procedures and communication protocols for their use. Second, they are to predict the performance of the human operator in the ATM system. In order to support these functions, we have developed a human/system model for advanced ATM operations that is a hybrid engineering control theoretic and cognitive performance model.

Engineering models of human performance have most successfully considered the human operator as a transfer function and remnant in a continuous control. They have concentrated on the interaction of one operator and a machine system with concern for system stability, accuracy of tracking performance, information processing of displays, and ability to handle disturbances. They are intended to provide guidance in design that determines whether the information provided, and the control system through which the operator performs their functions, allows successful performance with an acceptable level of effort (Baron and Corker, 1989). These models assume a closed-loop control in which the human operator observes the current state of the system, constructs a set of expectations based on his/her knowledge of the system (an internal model) modified by the most recent observation, and based on those expectations assigns a set of control gains or weighting functions that maximize the accuracy of a command decision.

In the context of air traffic management, such a representation needs to be expanded to include multiple operators in the system of control and to include the uniquely human contribution of adaptable, but potentially noisy, control input. The "noise" in this view of the operator is not a stationary Gaussian distribution. The specific description of this noise has potentially significant consequence. We have developed a hybrid model for multiple human operators in advanced ATM. In addition to concern for overall stability of the closed-loop management of air traffic, the model concerns itself with prediction of cognitive function. The specific characteristics of the human operator model are described in the paper.

In order to exercise the model we have simulated air-to-air self-separation scenarios based in a free-flight operational concept (Radio Technical Commission for Aeronautics (RTCA) 1995), and addressed the question of a required time to alert in airborne and ground control. The data for the human performance parameters of the model were derived from full-mission simulation studies conducted at NASA Ames Research Center. The implications of the model's prediction are discussed in terms of system stability in air-ground integration.

Fan, T., Hyams, D., and J. Kuchar, "Study of In-Flight Replanning Decision Aids," in *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, Boston, MA, August 10-12, 1998.

A four-stage conceptual model of the in-flight replanning decision process is presented. The four stages termed Monitor, Assess, Formulate, and Modify are discussed along with their interrelationships. Information elements used in each stage are defined and grouped into three modes: supplemental, thresholded, and guidance. Each mode describes the manner in which automation processes and presents the information to the pilot. Additionally, results from a survey of pilot preferences and decision-making behavior are summarized. From the survey, weather information is cited as the most common element consulted during replanning. A case study from the survey is also described in which the effect of pilot reports of turbulence on pilot decision-making is examined.

Hansman, R. J., Kuchar, J., Clarke, J. P., Vakil, S., Barhydt, R., and Pritchett, A., "Integrated Human-Centered Systems Approach to the Development of Advanced Cockpit and Air Traffic Management Systems," in *Proceedings of the 16th IEEE/AIAA Digital Avionics Systems Conference*, October 1997.

Human performance considerations are expected to be central to the performance of advanced cockpit and Air Traffic Management (ATM) systems. The development of information systems and decision aids in these advanced systems will be simultaneously driven by technical and human capabilities coupled with operational requirements. An integrated human centered systems approach is suggested which considers the human controller as a functional component of the closed-loop information system. Recent research activities which illustrate different aspects of human performance issues are discussed.

O'Hare, D., "The 'Artful' Decision-Maker: A Framework Model for Aeronautical Decision-Making," *The International Journal of Aviation Psychology*, 2(3), pp. 175-191, 1992.

The important role of good decision-making in aviation safety is now widely recognized. Although much effort has been devoted to the development of prescriptive models of aeronautical decision-making (ADM) and the preparation of training materials, very few attempts have been made to study actual decision-making processes of pilots. This article reviews the available literature of descriptive studies of ADM, as well as other examples of naturalistic decision-making in complex, dynamic environments. The process of ADM appears to differ in significant ways from the normative approach of decision analysis. A framework model of ADM is proposed and its compatibility with current artificial intelligence models of decision-making is discussed. The role of this descriptive model in directing future research into ADM and as a basis for further prescriptive efforts are highlighted.

Pisanich, G. and Corker, K., "A Predictive Model of Flight Crew Performance in Automated Air Traffic Control and Flight Management Operations," in *Proceedings of the Eighth International Symposium on Aviation Psychology,* Columbus, Ohio, 1995.

This paper describes Air-MIDAS, a model of pilot performance in interaction with varied levels of automation in flight management operations. The model was used to predict performance of a two-person crew responding to clearance information generated by the Center TRACON Automation System (CTAS). The model represents the information requirements, decision processes, communication processes, and motor performance required by the flight crew to integrate flight management automation and ground-side automation in clearance aiding.

Stochastic variations in environment and flight crew interruption were entered into the model, which them generated predictions of flight crew decision-making and clearance enactment strategies. The model's predictions were then compared to full-mission LOFT-type simulation data in which CTAS clearances were systematically varied in performance requirements and timing at top of descent. The paper describes the model, its development and implementation, the simulation test of the model predictions, and the empirical validation process. The complex human performance model allows variations in CTAS design to be explored through predictive simulation. Procedures and performance criteria as well as situational variations can be controlled and tested. The model and its supporting data provide a generalizable tool that is being expanded to include air/ground compatibility and ATC crew interactions in air traffic management.

Stokes, A. F., Kemper, K., and Kite, K., "Aeronautical Decision-Making, Cue Recognition, and Expertise Under Time Pressure," *Naturalistic Decision Making*, C. E. Zsambok and G. Klein, eds., Hillsdale, NJ, Lawrence Erlbaum Associates, Inc., pp. 183-196, 1997.

Used desktop flight simulation and cognitive (psychometric) testing to examine the adequacy of traditional views of decision-making within the context of aviation; examines the relationship of information-processing skills and knowledge representation measures to various stages in the decision-making process, including cue recognition and hypothesis generation. Subjects consisted of 24 pilots, 12 with considerable flight experience and 12 with relatively little. Although no artificial time limits or cutoffs were introduced into the pilots' task, the natural time pressure was enhanced.

Thurman, D. A., Chappell, A. R., and Mitchell, C. M., "An Enhanced Architecture for OFMspert: A Domain-Independent System for Intent Inferencing," in *Proceedings of the 1998 IEEE International Conference on Systems, Man, and Cybernetics*, pp. 955-960, 1998.

OFMspert is a computational software system to support operator intent inferencing in a wide range of domains and applications. This paper presents a brief history of OFMspert followed by a description of various enhancements resulting in the current domain- and application-independent architecture.

<u>NON-PILOT</u>.

Gray, W., John, B. E., and Atwood, M. E., "Project Ernestine: Validating a GOMS Analysis for Predicting and Explaining Real-World Task Performance," *Human-Computer Interaction*, 8(3), pp. 237-309, 1993.

Project Ernestine served a pragmatic as well as a scientific goal: to compare the work times of telephone company toll and assistance operators on two different workstations and to validate a Goals, Operators, Methods, and Selection rules (GOMS) analysis for predicting and explaining real-world performance.

Jacobs, J. L., Dorneich, M. C. P., and Jones, P. M., "Activity Representation and Management for Crisis Action Planning," in *Proceedings of the 1998 IEEE International Conference on Systems, Man, and Cybernetics*, pp. 961-966, 1998.

This work presents the development of a multiuser virtual environment in support of crisis management planning activities. Coupling ongoing work in activity representation with analysis of the crisis action planning domain, an extensible domain ontology was developed. Studying the domain, several challenges became apparent:

1. The need to support extensive dynamic and distributed collaboration.
2. The need for a flexible, open architecture.
3. The need for views of the information tailored to the activities of the planning team.
4. The opportunity to leverage past and current related efforts in the domain.

This project developed a Java-based collaboration architecture around a multiuser domain (MUD) to provide presence and access to collaborative services. The collaborative infrastructure layer provides persistence, user authentication, and access control. Built upon this substrate are collaborative services such as a whiteboard mechanism, chat functions, and the domain-specific Mission Analysis Support Tool (MAST). The target use of MAST is to represent and track workflow in the crisis action planning done by the Operations Planning Team of the U.S. Pacific Command.

The design approach was to base MAST on a reusable class library which implements a rich ontology structure and represents key elements of the domain. Our ontology draws on the SPOT project (Jacobs, J. L., Dorneich, M. C., Jones, P. M., O'Keefe, B. J., and Contractor, N., "SPOT: Using Collaborative Technologies For Developing Collaborative Technologies," in *Proceedings of the 1997 IEEE International Conference on Systems, Man, and Cybernetics*, pp. 690-695, 1997) and the Shared Planning and Activity Representation (SPAR) project. The resulting ontology, implemented in Java, is compliant with the SPAR Reference Object Model Specification. A strength of this work in the extensibility, flexibility, and openness both of the representation and the system architecture.

Kirlik, A., Miller, R. A., and Jagacinski, R. J., "Supervisory Control in a Dynamic and Uncertain Environment: A Process Model of Skilled Human-Environment Interaction," *IEEE Transactions on Systems, Man, and Cybernetics*, 23(4), pp. 929-952, 1993.

Presents a theory of interface-mediated human interaction with a dynamic, uncertain environment. The theory is applied to describing human-environment interaction in a multi-vehicle supervisory control task. In this context, a model is presented that explicitly represents the psychological processes of the human operator, the external task environment, and the

dynamic interaction between the human and the environment during the course of skilled activity. The model was able to mimic human behavior in a laboratory task requiring one- and two-person crews to direct the activities of a fleet of agents to locate and process valued objects in a simulated world. In the present theory, the environment is described as a dynamically varying set of action opportunities competing for the human's limited resources for cognition and action.

Klein, G. A., "The Recognition-Primed Decision (RPD) Model: Looking Back, Looking Forward," *Naturalistic Decision Making*, C. E. Zsambok and G. Klein, eds., Hillsdale, NJ, Lawrence Erlbaum Associates, Inc., pp. 285-292, 1997.

The recognition-primed decision (RPD) model has evolved during the past 10 yrs, addressing the issue of situation diagnosis, and becoming more clear about the nature of mental simulation. At the same time, the model has received empirical support both from researchers working in other domains and from testing hypotheses generated by the model. If the RPD model is expanded in the future, a possible direction will be the processes of option generation. The RPD model is an example of a naturalistic decision-making model. It attempts to describe what people actually do under conditions of time pressure, ambiguous information, ill-defined goals, and changing conditions.

Meyer, D. E. and Kieras, D. E., "A Computational Theory of Executive Cognitive Processes and Multiple-Task Performance: Part 2. Accounts of Psychological Refractory-Period Phenomena," *Psychological Review*, 104(4), pp. 749-791, 1997.

Computational models that are based on the executive-process interactive control architecture introduced by Meyer and Kieras (Meyer, D. E. and Kieras, D. E., "A Computational Theory of Executive Cognitive Processes and Multiple-Task Performance: Part 1," *Basic Mechanisms, Psychological Review*, 104, pp. 3-65, 1997) account well for patterns of reaction times and psychological refractory-period phenomena observed in a variety of laboratory paradigms and realistic situations.

Quinn, M. and Feher, B., "Simulation of Tactical Decision-Making by Warfare Commanders," in *Proceedings, Military, Government, and Aerospace Simulation*, 26(4), pp. 23-28, 1994.

Ryder, J. M., Weiland, M. Z., Szczepkowski, M. A., and Zachary, W. W., "Cognitive Engineering of a New Telephone Operator Workstation Using COGNET," in *Proceedings of the Human Factors and Ergonomics Society, 40th Annual Meeting*, Vol. 1, pp. 278-82, 1996.

Many cognitive engineering methodologies for user-centered design involve modeling procedural knowledge; others deal with domain semantics or conceptual models. COGNET (cognitive network of tasks) is a framework for modeling human cognition and decision-making which provides an integrated representation of the knowledge, behavioral actions, strategies, and problem solving skills used in a domain or task situation, yielding a powerful cognitive engineering tool. A case study of the design of the user interface for a new telephone operator workstation is presented to illustrate the derivation of the design from the components of the

COGNET model. The model does not directly convey any specific feature of the interface design, but rather a formal representation of the what the user must do with the resulting interface. This information is then evolved through a set of transformations which systematically move toward design features in a fully traceable manner.

Zachary, W., Le Mentec, J. C., Ryder, J., Ntuen, C. A., and Park, E. H., "Interface Agents In Complex Systems," *Human Interaction with Complex Systems: Conceptual Principles and Design Practice*, pp. 35-52, 1996.

It is argued that interface agent concepts and technology previously applied primarily to generic tasks, such as electronic mail management, are applicable to complex domain-based systems. Interface agents in these specialized domains require substantial amounts of domain-specific and task-specific knowledge in order to be useful to the system end-users. This makes their development potentially lengthy and costly. A way of removing this obstacle is to create a workbench for developing interface agents in complex domains. The paper describes research to create such a workbench, based on the COGNET framework for user-modeling (Zachary, W., Ryder, J., Weiland, M., and Ross, L., "Intelligent Human-Computer Interaction in Real-Time, Multi-Tasking Process Control and Monitoring Systems," *Human Factors In Design For Manufacturability*, M. Helander and M. Nagamachi, eds., New York: Taylor and Francis, pp. 377-402, 1992). COGNET is a well-established and validated technique for user cognitive modeling. A COGNET-based Generator of Intelligent Agents (GINA) workbench is described in which an agent-developer creates a cognitive model of a user's task/work strategy and automatically translates the model into an executable user model within a interface agent shell. Specific functionality is then added to allow the agent to use the embedded user model to reason about and help the system user perform tasks, solve problems, and manage attention. Examples of GINA-based agent applications in complex system environments are given.

TRAINING ARCHITECTURES

AVIATION.

Bechtel, R. J., "Air Combat Maneuvering Expert Systems Trainer," Merit Technology, Inc, final report AL-TP-1991-0058 under Contract F33615-88-C-0011, Jul. 88 - Dec. 91, 1992.

Chappell, A. R., Crowther, E. G., Mitchell, C. M., and Govindaraj, T., "The VNAV Tutor: Addressing a Mode Awareness Difficulty for Pilots of Glass Cockpit Aircraft," *IEEE Transactions on Systems, Man, and Cybernetics*, 27(3), pp. 372-385, 1997.

One of the major tasks of pilots of modern aircraft is monitoring and understanding the status and behavior of the auto-flight system, i.e., mode awareness. In order to maintain mode awareness in the dynamic environment, pilots must be continuously vigilant of indications from several locations within the cockpit. Lacking accurate and complete system knowledge and interfaces that clearly present the system state and constraints, pilots may misunderstand the control modes. Pilots often cite vertical path navigation (VNAV) as a flight management system function that surprises them. The VNAV Tutor, a computer-based training system, was developed to address

this issue. The VNAV Tutor attempts to improve the pilots' understanding of VNAV control modes and the interaction of the mode control panel functions with the flight management system during VNAV usage. An evaluation showed that the VNAV Tutor enhanced both the conceptual understanding and the operational use of the vertical navigation function by pilots transitioning to aircraft with sophisticated auto-flight systems.

Harper, K., Mulgund, S., Zacharias, G., and Kuchar, J., "Agent-Based Performance Assessment Tool for General Aviation Operations Under Free Flight," *AIAA Guidance, Navigation, and Control Conference*, Boston, MA, August 10-12, 1998.

The objective of this research is to design and demonstrate an agent-based modeling and analysis tool for evaluating general aviation (GA) pilot situation awareness under free-flight air traffic management (ATM). A computational tool is developed to assess free-flight's potential effect on GA operators, by combining an agent-based representation of the overall pilot/vehicle/ATM system with quantitative model-based metrics of pilot situational awareness (SA). The model's performance is demonstrated in a set of simulation trials designed to measure the pilot agent's ability to recognize and correctly assess protected zone conflicts in free-flight ATM using information available from a hypothetical cockpit display of information. A set of simulations is presented to examine the effect of sensor accuracy and attention allocation on pilot awareness of protected zone conflict hazards posed by intruder aircraft. The results show that reducing sensor accuracy leads to an increase in overall SA error and that the pilot agent divides its attention over multiple traffic hazards in proportion to each intruder's hazard potential. This attention sharing varies dynamically in a manner that is consistent with intuitive expectations as the conflict situation changes.

Ryder, J. M., Zachary, W. W., Zaklad, A. L., and Purcell, J. A., "A Design Methodology for Integrated Decision Aiding/Embedded Training Systems (IDATES)," US Naval Training Systems Center Technical Report 92-011, 1994.

Existing tools for decision aiding (DA) and embedded training (ET) are reviewed to determine their potential relevance for development of an integrated methodology. Current and planned Navy systems using DA and ET are reviewed to understand the range and types of systems that an integrated methodology should address. The IDATES cognitive model provides a theoretical basis for methodology development. Within the IDATES model, cognitive hierarchical levels of novice, intermediate, and expert are discrete stages that differ along two primary dimensions: problem representation and problem-solving procedure. There are two types of training: incremental and representational. A framework for an integrated methodology for designing DAs and ET is constructed.

Sherry, L. and Polson, P., "Annunciation and Training of Knowledge-Based Avionics," Honeywell Publication C69-5370-003, 1996.

Recent articles on the operations of avionics systems in highly automated air transports have described the operational complexity of the control modes and their annunciation and have documented operational and training issues:

1. Discrepancies between pilots' understanding and the actual operation of the avionics.
2. Controversies about the content and amount of training.
3. Controversies over the content and amount of information on the avionics interface.

Sherry and Polson (Sherry, L. and Polson, P.G., "A New Conceptual Model for Avionics Annunciation," *Institute of Cognitive Science Technical Report* 95-08, Boulder: University of Colorado, 1995) conclude that a root cause of these issues is the lack of a complete model of the organization and behavior of the avionics software shared by pilots, the avionics software, and design engineers. This paper introduces a new model, the operational procedure model, of the avionics for highly automated air transports. The operational procedure model represents the mission, the rules, and the functions of modern avionics systems.

The avionics software is knowledge based. The decisions made by each of the avionics are based on a model of the mission. The behavior of the software is dominated by the rules of decision-making logic that performs functions required by each task. This model has been defined such that it can be understood and shared by pilots, by avionics software, and by design engineers. Each element of the software is defined in terms of its intent (what?), the rationale (why?), and the resulting behavior (how?). The resulting model of the avionics system can be employed to design superior forms of annunciation (feedback) and interactive computer-based training.

<u>NON-PILOT</u>.

Chu, R. W., Mitchell, C. M., and Jones, P. M., "Using the Operator Function Model and OFMspert as the Basis for an Intelligent Tutoring System: Towards a Tutor/Aid Paradigm for Operators of Supervisory Control Systems," *IEEE Transactions on Systems, Man, and Cybernetics*, 25(7), pp. 1054-1075, 1995.

Training is a critical issue for operators responsible for the safe and efficient operation of large-scale complex dynamic systems. This paper proposes and articulates a set of requirements for an intelligent tutoring system. The requirements specify what (instructional content) and how (instructional strategies) to teach a novice operator to supervise and control a complex dynamic system. The instructional content teaches system structure and behavior (i.e., declarative knowledge), system procedures (i.e., procedural knowledge), and how to use this declarative and procedural knowledge to manage a complex dynamic system in real time (i.e., operational skill). Using the underlying representations of the operator function model (OFM) and OFMspert, the OFM's computational implementation, GT-VITA (Georgia Tech Visual and Inspectable Tutor and Assistant) realizes these requirements. As a proof-of-concept demonstration, an instance of the generic GT-VITA tutoring architecture was implemented for satellite ground controllers. The empirical evaluation, utilizing NASA satellite ground control personnel, showed that GT-VITA was a flexible and useful training system. In fact, NASA has adopted VITA as the foundation for required training for all satellite ground control personnel. In addition to an intelligent tutoring system architecture, by using and extending the operator function model and OFMspert, GT-VITA demonstrates a robust methodology for conceptualizing the tutor-aid paradigm. The tutor-aid paradigm defines a conceptual framework in which learning with an intelligent tutor gradually becomes collaboration with an intelligent associate. Using the same structures (i.e.,

OFM and OFMspert) and the same domain knowledge, GT-VITA specifies a tutor and GT-MOCA (Jones, P. M. and Mitchell, C. M., "Human-Computer Cooperative Problem Solving: Theory, Design, and Evaluation of an Intelligent Associate," *IEEE Transactions on Systems, Man and Cybernetics*, 25(7), pp. 1039-1053, 1995) specifies an aid.

Katz, S., Lesgold, A., Hughes, E., Peters, D., Eggan, G., Gordin, M., and Greenberg, L., "Sherlock 2: An Intelligent Tutoring System Built on the LRDC Tutor Framework," *Facilitating the Development and Use of Interactive Learning Environments*, C. P. Bloom and R. B. Loftin, eds., Hillsdale, NJ, Lawrence Erlbaum Associates, 1997.

Describes the development of Sherlock 2, an intelligent tutoring system (ITS) built on the Learning Research and Development Center (LRDC) tutor framework, as a training tool for the US Air Force. After a brief introduction to the tutoring system, the authors describe the LRDC tutor framework that provides the core system architecture as well as the basic ITS services that it runs on (e.g., coaching, domain expertise, simulation of the task domain, and data management). The authors then focus on the two services that they believe are the most critical for making an ITS behave intelligently: simulations of the task domain and of a domain expert, which can model skilled behavior for students and work with the system's coach to help students acquire domain knowledge and skills. The discussion of these components of the LRDC tutor framework emphasized the lesson the authors learned about how to design, develop, and customize the simulation and coaching services for a particular tutor. Finally, they comment more broadly on the lessons they learned about how to gain and sustain acceptance of a tutoring system during field trials and the early stages of deploying Sherlock 2.

Lesgold, A., Lajoie, S., Bunzo, M., and Eggan, G., "SHERLOCK: A Coached Practice Environment for an Electronics Troubleshooting Job," *Computer-Assisted Instruction and Intelligent Tutoring Systems: Shared Goals and Complementary Approaches*, J. H. Larkin and R. W. Chabay, eds., Hillsdale, NJ, Lawrence Erlbaum Associates, 1992.

SHERLOCK is a computer-based supported practice environment for a complex troubleshooting job in the Air Force. The chapter describes the training problem for which SHERLOCK was developed, the principles behind its development, and its implementation. It describes SHERLOCK's task domain—the electronic troubleshooting task. It discusses the principles guiding SHERLOCK's development followed by examples of how experts and trainees think about the troubleshooting task and of how SHERLOCK interacts with a trainee. It also describes SHERLOCK's implementation and its relation to some general pedagogical issues.

Stone, D. R., "Airborne Warning and Control System (AWACS) Intelligent Tutoring System," final report F33615-87-D-0601, 1993.

Tate, D. L., "Development of a Tactical Decision Aid for Shipboard Damage Control," final report NRL/FR/5580-96-9837, 1996.

Zachary, W., Ryder, J., Hicinbothom, J., and Bracken, K., "The Use of Executable Cognitive Models in Simulation-Based Intelligent Embedded Training," in *Proceedings of 41st Meeting of the Human Factors and Ergonomics Society*, Vol. 2, pp. 1118-22, 1997.

This paper defines a new role for expert models in intelligent embedded training-guiding practice. The integration of problem-based practice with focused, automated instruction has long proven elusive in training systems for complex real-world domains. The training strategy of guided practice offers a way to merge the approaches of traditional simulation-based practice and intelligent tutoring's knowledge tracing. The performance of the trainee is dynamically assessed against scenario-specific expectations and performance standards, which are generated during the simulation by embedded models of expert operators. This research developed an executable cognitive model capable of solving realistic simulation scenarios in an expert-level manner, identified and implemented modifications and extensions to this baseline model needed to generate dynamic and adaptive expectations of future trainee actions, and developed means of providing cognitive state information for use in (separate) diagnostic processes, without resorting to full-scale knowledge tracing methods.

DISPLAY MANAGEMENT/DESIGN

AVIATION.

Battiste, V. and Johnson, W. W., "Development of a Cockpit Situation Display for Free-Flight," Society of Automotive Engineers, Inc., 1998.

Endsley, M. R. and Selcon, S. J., "Designing to Aid Decisions Through Situation Awareness Enhancement," in *Proceedings for the Second Annual Symposium and Exhibition on Situational Awareness in the Tactical Air Environment*, pp. 107-112, 1997.

Automation and various forms of artificial intelligence have been the focus of concerted efforts in cockpit development over the past 2 decades. Work in this area largely has been focused on the problems of high workload in the cockpit—either as an affect of reduced crew size or increased complexity of missions and avionics systems. In addition, these systems typically strive to increase the effectiveness and reliability of operator decision-making.

Due to the difficulties in combining decisions from human operators and machines and due to reductions in situation awareness (SA) that have been found with automated systems, our approach is to seek to improve decision-making by focusing on improving SA. Systems which help operators to achieve high levels of SA are likely to achieve the desired decision-making and overall performance improvements.

An investigation of a system for directly presenting needed SA to fighter pilots was conducted. The study also supports the utility of using a test-battery approach for evaluating display concepts.

Feary, M., McCrobie, D., Alkin, M., Sherry, L., and Polson, P., "Aiding Vertical Guidance Understanding," NASA/TM-1998-11221, National Aeronautics and Space Administration, Moffett Field, CA, Ames Research Center, 1998.

A two-part study was conducted to evaluate modern flight deck automation and interfaces. In the first part, a survey was performed to validate the existence of automation surprises with current pilots. Results indicated that pilots were often surprised by the behavior of the automation. There were several surprises that were reported more frequently than others. An experimental study was then performed to evaluate (1) the reduction of automation surprises through training specifically for the vertical guidance logic and (2) a new display that describes the flight guidance in terms of aircraft behaviors instead of control modes. The study was performed in a simulator that was used to run a complete flight with actual airline pilots. Three groups were used to evaluate the guidance display and training. In the training condition, participants went through a training program for vertical guidance before flying the simulation. In the display condition, participants ran through the same training program and then flew the experimental scenario with the new Guidance-Flight Mode Annunciator (G-FMA). Results showed improved pilot performance when given training specifically for the vertical guidance logic and greater improvements when given the training and the new G-FMA. Using actual behavior of the avionics to design pilot training and FMA is feasible, and when the automated vertical guidance mode of the Flight Management System is engaged, the display of the guidance mode and targets yields improved pilot performance.

Geddes, N. and Hammer, J. M., "Automatic Display Management Using Dynamic Plans and Events," in *Proceedings of the 6th International Symposium on Aviation Psychology*, pp. 90-95, 1991.

A flexible and powerful approach to automatic management of computer-based displays and controls has been developed as a part of the intelligent Pilot Vehicle Interface (PVI) for the USAF/Lockheed Pilot's Associate. Because the active information requirements are maintained dynamically as the system is operated, the automatic selection of display formats and control functions can be sensitive to the exact tasks and situations of the pilot. The generality of the display management process suggests that it can be easily applied in a wide variety of situations in which management of large volumes of time-sensitive information is an issue for effective system operation.

Lintern, G., Roscoe, S. N., and Sivier, J. E., "Display Principles, Control Dynamics, and Environmental Factors in Pilot Training and Transfer," *Human Factors*, 32(3), pp. 299-317, 1990.

Sixty-four flight-naïve men were tested in a fractional factorial, quasi-transfer experiment to examine the effects of four display factors, one control response factor, and one environmental factor on acquisition and transfer of aircraft landing skills. An additional 12 trainees served as experimental controls. Transfer was measured from each of 64 experimental training conditions to a criterion condition with a conventional inside-out pictorial contact display, normal simulator control dynamics, and a 5-knot crosswind. Transfer was better following training with pictorial

displays than with symbolic displays and with normal rather than reduced bank control order. Interactions of crosswind with predictive augmentation and with bank control order showed that for some conditions, transfer benefited from training with predictive augmentation and from training without crosswind.

Lintern, G., Taylor, H. L., Koonce, J. M., Kaiser, R. H., and Morrison, G. A., "Transfer and Quasi-Transfer Effects of Scene Detail and Visual Augmentation in Landing Training," *The International Journal of Aviation Psychology*, 7(2), pp. 149-169, 1997.

Beginning flight students were taught landings in a flight simulator with a visual landing display to examine the effects of scene detail, visual augmented guidance, and number of landing training trials. Some students were trained in a control condition with no visual display. Transfer was assessed in the airplane in relation to the amount of landing training required prior to release for solo. Training with a low-detail scene was better for transfer than was training with a moderate-detail scene. An interaction between scene detail and augmented guidance showed that augmented guidance enhanced transfer when used in training with low-detail scene but degraded transfer when used in training with a moderate-detail scene. The data also show that both visual and nonvisual training in the simulator build skills that enhance transfer.

Mykityshyn, M., Kuchar, J., and Hansman, R. J., "Experimental Study of Electronically Based Instrument Approach Plates," *The International Journal of Aviation Psychology*, Vol. 4, No. 2, pp. 141-166, 1994.

Issues associated with the electronic presentation of instrument approach plates (IAPs) were investigated in a part-task simulation study. Several electronic IAP chart formats were developed and evaluated. A decluttering system that allowed the pilots to selectively suppress various information groups in some of the prototype formats was also investigated. Results of the experimental study indicated that there was no degradation and possibly a limited gain in information-retrieval performance when IAP information was presented in electronic format and compared to traditional paper IAPs. Each pilot preferred the selectable decluttering feature. The preferred chart was a color, north up (nonmoving map) format with a decluttering capability. During the simulation, low levels of terrain situational awareness were observed when pilots were given erroneous air traffic control vectors toward hazardous terrain.

Vakil, S., Hansman, R. J., Midkiff, A., and Vaneck, T., "Feedback Mechanisms to Improve Mode Awareness in Advanced Autoflight Systems," in *Proceedings of the Eighth International Symposium on Aviation Psychology*, pp. 243-248, April 1995.

An examination of autoflight systems in modern aircraft was made, with emphasis on the complex mode structure which is suspect in several recent accidents. Aviation Safety Reporting System reports and Flight Mode Annunciator conventions were examined. Focussed interviews with pilots and check airmen were conducted. Principal results identified the lack of a consistent global model of the Autoflight System architecture and identified the vertical channel as requiring enhanced feedback. Functional requirements for an Electronic Vertical Situation Display (EVSD) were created based on established conventions and identified mode awareness

problems. A preliminary version of this display was prototyped and an evaluation methodology was proposed.

Webb, B.W., Geddes, N.D., and Neste, L.O., "Information Management With a Hierarchical Display Generation," *NCGA '89 Conference Proceedings, 10th Annual Conference and Exposition Dedicated to Computer Graphics*, Vol. 1, pp. 52-62, 1989.

Typical current practices in information analysis and display format design are based on the notion that the resulting display generation software must produce fixed format representations of information on the physical display medium. This paper describes a novel alternative approach in which the display software is capable of creating a very large variety of representations of information on the physical display device. The display software is controlled by an intelligent information manager program that selects and tailors the actual display formats during execution to produce information displays optimized for the specific tasks currently being performed by the operator of the system. This approach has been used in a complex aerospace application to dramatically reduce the need for manual selection and control of the display formats. This feature is expected to be of significant benefit in any system in which the human operator must manage a large amount of information under time-critical conditions.

<u>NON-PILOT</u>.

Adelman L., Cohen, M. S., Bresnick, T. A., Chinnis, J. O., and Laskey, K. B., "Real-Time Expert-System Interfaces, Cognitive Processes, and Task Performance: An Empirical Assessment," *Human Factors*, 35(2), pp. 243-261, 1993.

In this experiment we investigated the effect of different real-time expert system interfaces on operators' cognitive processes and performance. The results supported the principle that a real-time expert-system's interface should focus operators' attention on where it is required most. However, following this principle resulted in unanticipated consequences. In particular, it led to inferior performance for less critical, yet important, cases requiring operators' attention. For such cases, operators performed better with an interface that let them select where they wanted to focus their attention. Having a rule generation capability improved performance with all interfaces but did so less than hypothesized. In all cases, performance with different interfaces and a rule generation capability was explained by the effect of the interfaces on cognitive process measures.

Kirlik, A., "Requirements for Psychological Models to Support Design: Toward Ecological Task Analysis," *Global Perspectives on the Ecology of Human-Machine Systems*, J. Flach, P. Hancock, J. Caird, and K. Vicente, eds., Hillsdale, NJ, Lawrence Erlbaum Associates, Vol. 1, 1995.

The chapter identifies a set of necessary conditions for psychological models capable of supporting the design of environments to promote skillful and effective human activity. This effort is motivated by my own limited success in attempting to apply the products of cognitive science to cognitive engineering. It is suggested that the necessary conditions for an acceptable

psychological model in cognitive science are quite different than the necessary conditions for a psychological model capable of guiding design. The solution to the problem of creating a scientific basis for cognitive engineering is not merely one of improving the designer's access to research findings, moving research into naturalistic or operational contexts, or improving generalizability from experimental results (although each of these goals is surely important). I suggest that the solution must lie in a reformulation of the questions posed by basic psychological research itself. A reformulation driven by an understanding of the psychological nature of the design product and the knowledge that is required to create itself:

- the psychological nature of the design product
- modeling to support design
- issues in environmental modeling (modeling the integrated human-environment system, the need for models of fluent interaction with the world)

A move toward an ecological perspective is suggested as well as a framework for ecological task analysis. An example ecological task analysis is provided.

Mitchell, C. M. and Saisi, D. L., "Use of Model-Based Qualitative Icons and Adaptive Windows in Workstations for Supervisory Control Systems," *IEEE Transactions on Systems, Man, and Cybernetics*, 17(4), pp. 573-593, 1987.

Qualitative icons and windowing technology have been combined and implemented in an operator interface to the Georgia Tech-Multisatellite Operations Control Center (GT-MSOCC). An operator function model for GT-MSOCC was used to derive workstation features including hardware configuration, the function of qualitative icons for monitoring, fault detection and identification, and the contents and placement of computer windows. The model also determined sets of windows needed by the operator to undertake major operator control functions. An experiment was performed to evaluate the effectiveness of a workstation incorporating model-based qualitative icons and dynamic operator-function window sets. Eleven measures that reflected operator performance were analyzed. Subjects using the model-based workstation operated the system significantly better on nine of these measures. On all measures, performance with the model-based workstation was uniformly better on average and had less variability than performance with the conventional workstation.

MISCELLANEOUS

Baillie, S., Morgan, J. M., Mitchell, D., and Hoh, R., "The Use of Limited Authority Response Types to Improve Helicopter Handling Qualities During Flight in Degraded Visual Environments," *American Helicopter Society Proceedings of 1995, 51st Annual Forum*, Vol. 2, Part 2, pp. 1717-1728, May 9-11, 1995.

The concept and rationale behind developing a Limited Authority Response Type (LART) to improve handling qualities of a helicopter for operations in degraded visual environments (DVE)

is explained. A LART may be achieved by reprogramming existing, limited authority stability augmentation system actuators to produce a moderate bandwidth, low-authority attitude response type. Selected results from a piloted handling qualities experiment—conducted on the NRC Bell 205 Airborne Simulator—addressing this concept are presented. This experiment examined the handling qualities of a UH-60-like helicopter with various LART systems while conducting operations in poor night vision goggle conditions. The results indicate an improvement in handling qualities for systems with attitude authority as low as 2.5 degrees and a general dislike of systems using parallel servos to increase the overall attitude authority. Provision of a pilot selectable height hold system during flight in DVE provided the greatest handling qualities improvement. Pilot comments and some inconsistent results suggest more detailed research is required to confirm the results prior to practical applications of the concept.

Baldwin, J. and Smith, A., "GPS Application to General Aviation Collision Avoidance," *Proceedings of the National Technology Meeting, Institute of Navigation, Navigating the Earth and Beyond*, pp. 315-321, Jan. 24-26, 1994.

This paper describes the application of global positioning system (GPS) to the FAA's safety mission of traffic collision avoidance, specifically to GA.

TCAS I—which alerts pilots to nearby aircraft—is now being installed by the commuter airlines, but its sophisticated design and comparatively high cost has restricted more extensive use. Small airplanes have so far had limited access to the TCAS safety net and, depending on their transponder equipage, are not always detected by airliners or by ground surveillance systems. The U.S. Department of Transportation has awarded a Small Business Innovative Research contract to Rannoch for the development of a small, low-cost general aviation cockpit device aimed at enhancing air safety by combining Mode S and GPS technology. This paper presents the issues and challenges of designing a system that will satisfy the needs of general aviation and the TCAS community.

Nothing contained within this paper is intended to reflect the official position or view of the TCAS Program Office. This paper reflects only the understanding and views of the authors.

Baldwin, J., Smith, A., and Cassell, R., "General Aviation Collision Avoidance - Challenges of Full Implementation," *IEEE/AIAA Digitial Avionics System Conference: Proceedings of 1994 IEEE/AEA*, pp. 504-509, Oct. 30 - Nov. 3, 1994.

This paper discusses the requirements for surveillance and collision avoidance equipment in the National Airspace System (NAS), the current avionics equipage by the U.S. aircraft fleet, and the GA avionics market in general. The operational and functional requirements for a general aviation traffic alert system are presented accompanied by concept design, development, and schedule information. The paper also discusses the issue of achieving compatibility with the existing Traffic Alert and Collision Avoidance System (TCAS) community. This paper contains only the understanding and views of the authors and is not intended to reflect the official position or view of the U.S. Government or Federal Aviation Administration (FAA).

Baldwin, J., Cassell, R., and Smith, A., "GPS-Based Terrain Avoidance Systems - A Solution for General Aviation Controlled Flight Into Terrain," *Proceedings of the Annual Meeting - Institute of Navigation, Navigating the 90's*, pp. 413-417, Jan. 18-20, 1995.

Of the 2533 fatal general aviation (GA) accidents from 1982-1988, a total of 646 fatal accidents (nearly 26%) were attributed to controlled flight into terrain (CFIT). This category of accident was the single biggest cause of GA aircraft fatalities during this period. This paper discusses a concept for a low-cost GA Ground Proximity Warning System (GPWS) that can satisfy the operational requirements for avoiding CFIT incidents; thereby improving the utility and safety of GA flight activities. The results from this work are expected to validate the concept of operation, determine the functional and physical characteristics of the device, and validate the design through modeling and simulation. Assuming a successful conclusion to the concept validation stage, fabrication of a preliminary hardware prototype will also be initiated in preparation for flight testing.

The device relies on two extensive databases and a GPS sensor to develop a low-cost GPWS designed specifically for the, small, single-engine, single-pilot GA aircraft—referred to as the TWAS (Terrain Warning and Avoidance System).

Barrows, A., Enge, P., Parkinson, B., and Powell, J. D., "Flight Tests of a 3-D Perspective-View Glass-Cockpit Display for General Aviation Using GPS," *Proceedings of the 1995 8th International Tech. Meeting of the Satellite Division of the Institute of Navigation*, Vol. 2, Part 2, pp. 1615-1622, Sept. 12-15, 1995.

A display that takes advantage of the three-dimensional positioning data available from differential GPS has been flight tested on a general aviation aircraft. This glass-cockpit instrument provides a natural, "out the window" view of the world, making the horizon, runway, and desired flight path visible to the pilot in instrument flight conditions. The flight path is depicted as a series of symbols through which the pilot flies the airplane. Altitude, heading, and airspeed are presented along with lateral and vertical glidepath deviations. Particular attention was given to demonstrating a system satisfying the budget, power, and form-factor constraints of light aircraft.

Simulator tests and flight trials on a Piper Dakota aircraft allowed that the tunnel display allows the pilot to hand fly straight-in approaches with equivalent or better flight technical error than with a typical Instrument Landing System (ILS) needle display. Additionally, the tunnel display provides lateral and vertical guidance on curving missed approach procedures, for which ILS cannot provide positive course guidance. The results demonstrate that GPS-based displays can improve navigation along straight and curving flight paths in light aircraft by enhancing pilot situational awareness. Better path-following accuracy will benefit future Air Traffic Control schemes and a variety of specialized applications.

Barrows, A., Enge, P., Parkinson, B., and Powell, J. D., "Flying Curved Approaches and Missed Approaches: 3-D Display Trials Onboard a Light Aircraft," *Proceedings of the 1996 9th*

International Tech. Meeting of the Satellite Division of the Institute of Navigation, Vol. 1, Part 1, pp. 59-68, Sept. 17-20, 1996.

Cockpit displays that enhance situational awareness in light aircraft are becoming feasible through the rapid development of enabling technologies including differential GPS, inexpensive computers, and ruggedized color LCD panels. A prototype glass-cockpit system was developed and used to explore implementation and operational issues through flight testing. The display provided an "out the window" three-dimensional (3-D) perspective view of the world, making the horizon, runway, and desired flight path visible to the pilot even in instrument flight conditions. The desired flight path was depicted as a tunnel through which the pilot flew the airplane. Predictor symbology was added in response to pilot requests for better guidance and presentation of path-following errors.

Piloted simulations and flight tests on a four-seat Piper Dakota demonstrated enhanced accuracy and capability on a variety of trajectory types. These included curved approaches with one constant-radius turn, segmented approaches, and complex missed approaches with multiple curved segments, climbs, and descents. Flight technical error and position histories document system performance. Hardware, sensors, and computational issues specific to the problem of practical 3-D perspective flight displays are discussed. The results demonstrate that an intuitive display can allow precise navigation on complex flight paths and increase safety through improved situational awareness. In addition to enhancing typical passenger aircraft operations, such systems would be valuable for applications requiring precise path following in low-visibility situations.

Barrows, A., Gebre-Egziabher, D., Hayward, R., Xia, R., and Powell, J. D., "GPS-Based Attitude and Guidance Displays for General Aviation," *IEEE Symposium on Emerging Technology of Factory Automation, ETFA Proceedings of the 1996 IEEE Conference on Emerging Technology of Factory Automation*, pp. 423-428, Nov. 18-21, 1996.

GPS was used with a short-baseline (1 and 2 wavelengths), triple-antenna configuration to obtain attitude in conjunction with solid state rate gyros. The system was used to provide an inexpensive Attitude·Heading Reference System (AHRS) for use by small General Aviation aircraft. The gyros enabled a high bandwidth output while the GPS was used to estimate the gyro drift rate. The resulting attitude information was used, along with GPS-based position, by a graphical out-the-window view with tunnels indicating the desired path in the sky for the current phase of flight. Accuracy and ease of flying are enhanced by the system.

Battiste, V. and Delzell, S., "Visual Cues to Geographical Orientatron During Low-Level Flight," *Proceedings of International Symposium of Aviation Psychology*, pp. 566-571, Apr. 29 - May 2, 1994.

Battiste, V. and Downs, M., "Development of a Navigation/Situation Display to Improve Aerial Fire Fighting Safety and Efficiency," *Proceedings of the Human Factors and Ergonomics Society, 39th Annual Meeting*, Vol. 2, Part 2 (2), pp. 1175-1179, Oct. 9-13, 1995.

Aerial firefighting is a high-risk, high-cost aviation environment. Normal aviation risks are magnified, sometimes significantly, by a number of factors. Over the years a number of accidents (midair collisions and controlled flight into terrain), near midair collisions, and other serious incidents involving firefighting aircraft have occurred. The causes of these accidents or incidents have been primarily attributed to loss of situational awareness in the relatively unstructured aerial environment surrounding wildland fires. In an effort to improve safety and efficiency, researchers at NASA Ames Research Center are working with aerial firefighters to develop a standard phraseology, air space structure, and a navigational situation display. This paper will focus on the results of an initial communication analysis and will present a prototype airspace structure and the preliminary design and evaluation of the navigation/situation display.

Battiste, V., Downs, M., and McCann, R., "Advanced Taxi Map Display Design for Low-Visibility Operations," *Proceedings of the Human Factors and Ergonomics Society 1996, 40th Annual Meeting*, Vol. 2, Part 2(2), pp. 997-1001, Sept. 2-6, 1996.

Conducting gate-to-gate operations during reduced visibility conditions is a major impediment to scheduled and unscheduled flight operations in the National Airspace System (NAS). Takeoff and landing minima are predicated on aircraft equipage and airport visibility (e.g., at some major airports, operations are terminated when visibility is below 700 A runway visual range (RVR). Although some aircraft can land with zero-zero visibility, there are no ground or flight deck systems that allow them to taxi under low-visibility conditions. A map display system designed to support low-visibility taxi was evaluated by 12 B-747 flight crews in NASA's Crew Vehicle System Research Facility (CVSRF). Three taxi-map conditions were compared: paper map only, basic moving map, and advanced moving map. Crews landed and taxied along 24 different taxi routes under three visibility conditions: unlimited visibility, 700-ft RVR, and 300-ft RVR. Taxi time, errors, and workload were collected for each taxi operation. Video tape recordings captured crew interactions and head-up and head-down times. Taxi times, and errors were significantly better for crews with electronic maps than for crews with a paper map. Although crews with the advanced map experienced significantly more head-down time, the head-down interval was significantly less than with the paper map, and crew workload was significantly less. During the postflight design review, pilots identified improvements in procedures and formatting that might enhance performance. They developed a procedure for safely switching from the NAV display to the map, and in general their comments were very favorable.

Beringer, D., "Issues in Using Off-the-Shelf PC-Based Flight Simulation for Research and Training: Historical Perspective, Current Solutions, and Emerging Technologies," *Proceedings of the Human Factors Society, 39th Annual Meeting*, Vol. 1, part 1(2), pp. 11-15, Oct. 9-13, 1995.

Flight simulation has historically been an expensive proposition, particularly if out-the-window views were desired. Advances in computer technology have allowed a modular, off-the-shelf flight simulation (based on 80486 processors) to be assembled that has been adapted with minimal effort for conducting general-aviation research. This simulation includes variable flight instrumentation, forward, 45- and 90-degree left external world views and a map display. Control inputs are provided by high-fidelity analog controls (e.g., damped and self-centering

yoke; high-performance throttle quadrant; gear, flap, and trim controls; and navigation radio frequency select). The simulation is based upon two commercially available flight simulation software packages, one designed as an instrument flight trainer and the other as a game-type flight simulation. The provisions of these packages are discussed highlighting their particular research capabilities as well as their limitations. The comparatively low cost and ease of assembly/integration allow multiple standardized systems to be distributed for cooperative interlaboratory studies. The approach appears to have utility for both research and training. Preliminary experimental results are reported as a validation of the utility of the system for research.

Beringer, D. and Harris, H. C., Jr., "Navigation Display Integration in the General Aviation Environment: Performance Using the Horizontal Situation Indicator," *Proceedings of the Human Factors Society, 39th Annual Meeting*, Vol. 1, part 1(2), pp. 11-15, Oct. 9-13, 1995.

Much effort has been invested in examining integrated instrumentation for advanced aircraft cockpits, but little comparable effort has been directed toward the greatest number of aircraft presently flying—those in the general aviation environment. This study examined the benefits of a simple and widely available integrated instrument, the horizontal situation indicator (HSI), in the performance of simple navigation and orientation tasks by private pilots. Tested in the context of the multiple-processor Basic General Aviation Research Simulator (BGARS), pilots exhibited significantly fewer navigational reversals and orientational errors when using the HSI (in comparison with their performances when using the traditional VOR and Directional Gyro combination). These results were consistent with but even more definitive than an earlier sample of instructor pilots. Similar benefits in procedural error reduction were also found when instrument index markers, or bugs, were used as short-term memory aids.

Berman, Z., Rafael, H., and Powell, J. D., "The Role of Dead Reckoning and Inertial Sensors in Future General Aviation Navigation," *IEE 1998 Position Location and Navigation Symposium*, pp. 510-517, April 20-23, 1996.

Possible configurations for a general aviation autonomous navigation system are studied. Doubtless, an advanced GPS receiver is a must have system component. GPS has had some outages due to unintentional interference or even intentional jamming, and aircraft should be able to navigate through such an event. Natural candidates for GPS backup are inertial sensors, magnetic compass, and airspeed sensors. All these sensors can be calibrated during GPS availability. Moreover, for dead reckoning systems, wind velocity can be estimated as well. This paper presents an original statistical model for wind variations that matches actual data very well. Using this model and a parametric family of inertial measurement sensors, horizontal position errors during a GPS outage are compared for a variety of configurations: a dead reckoning system, stand alone inertial sensors, and inertial sensors integrated with the dead reckoning system.

Bussolari, S. and Bernays, D. J., "Mode S Data Link Applications for General Aviation," *IEEE, 1995*, 0-7803-3050-1/95, pp. 199-206.

The Mode S data link is a high-capacity air/ground digital communications system that can deliver information to the cockpit in a form that will significantly improve pilot situational awareness and aircraft utility. The FAA is deploying Mode S surveillance sensors with data link capability at 143 sites across the United States. Three Mode S data link applications: Traffic Information Service, Text Weather Service, and Graphical Weather Service have been developed to meet the specific needs of General Aviation. Traffic Information Service uses the surveillance capability inherent in the Mode S sensor to provide the pilot with a display of nearby traffic. Text Weather Service and Graphical Weather Service provide a means to deliver real-time weather text and graphics to the cockpit. An additional Mode S data link application, the use of the Mode S squitter for Automatic Dependent Surveillance Broadcast (ADS-B), also offers significant benefits to GA. Low-cost avionics have been developed to support these and other Mode S data link applications for General Aviation.

Chandra, D., Bernays, D. J., and Bussolari, S. R., "Field Evaluation of Data Link Services for General Aviation," 0-7803-3050-1/95, 1995 IEEE, pp. 258-263.

With the sponsorship of the Federal Aviation Administration, MIT Lincoln Laboratory has developed data link traffic and weather services for general aviation: The Traffic Information Service (TIS) displays ground-based traffic information; the Graphical Weather Service (GWS) disseminates graphical precipitation maps; and the Text Weather Service (TWS) provides surface observations and terminal forecasts.

Development of the data link applications has now reached the field evaluation stage. Plans are to equip a limited number of light aircraft with the data link avionics for a 6-month period. The services are provided via the Dulles International Airport Mode S sensor and a ground transmit/receive station installed in Frederick, MD. Pilot evaluators have access to the services on structured evaluation flights and routine business flights. Evaluators will assess each of the services, the training procedures, and the cockpit interface.

Cobb, H. S., Lawrence, D., Pervan, B., Cohen, C., Powell, J. D., and Parkinson, B., "Precision Landing Tests with Improved Integrity Beacon Pseudolites," *Proceedings of ION GPS-95: 8th International Technical Meeting of the Satellite Division of the Institute of Navigation*, pp. 827-833, Sept. 12-15, 1995.

Stanford University's Integrity Beacon Landing System (IBLS) uses ground-based pseudo-satellite transmitters known as Integrity Beacons to resolve carrier phase ambiguities on final approach, giving IBLS both high integrity and centimeter-level accuracy. This paper discusses two improved Integrity Beacon designs and the results of flight tests with these new beacons.

The original Integrity Beacons were not synchronized to GPS time. The IBLS reference station was required to measure the beacon carrier phase reference information using a direct cable connection to each Integrity Beacon. This proved inconvenient in practice. Therefore, a pair of Autonomous Integrity Beacons were constructed, pseudolites whose transmitted signals are synchronized to GPS satellite signals using the Omni-Marker principle invented at Stanford

University. Flight tests using these beacons showed that IBLS performance was maintained with the reference station in a convenient location some 6 kilometers from the beacons.

The original Integrity Beacons produced a short-range "bubble" of usable signals. While this was sufficient to demonstrate the IBLS concept, a longer-range beacon would have additional applications. To this end, an Autonomous Integrity Beacon was constructed with a range greater than 4 kilometers using a pulsing scheme similar to that recommended by RTCM-104 to alleviate the near/far problem. Flight tests showed that this long-range beacon provided useful information to IBLS everywhere within its expanded bubble without blocking satellite reception by IBLS or conventional GPS receivers.

Gazit, R. and Powell, J. D., "The Effect of a GPS-Based Surveillance on Aircraft Separation Standards," *Proceedings of the IEEE Position Location and Navigation Symposium*, pp. 360-367, Apr. 22-26, 1996.

The current aircraft separation standards are based in part on the surveillance accuracy of radar measurements. This study estimates the effect of GPS-based surveillance on the separation standards, assuming that every aircraft periodically broadcasts its position as derived by an onboard GPS receiver. The position reports are received by ground controllers and are used for aircraft tracking and conflict resolution.

Based on the probability distribution functions of GPS and radar measurement errors, the probability of a close approach between aircraft is computed and a new separation standard derived that will keep the current safety level. By applying similar arguments, an estimate of the effect of GPS-based surveillance on the minimum runway separation that is required for conducting independent parallel approaches under instrument meteorological conditions can be made.

The various elements of the required runway spacing are analyzed and studied for the possible use of velocity estimate in predicting future conflicts. The tradeoff between the probability of false alarm and the probability of late alarm and its effect on the required spacing is studied by using a Monte Carlo simulation.

Gazit, R. and Powell, J. D., "Aircraft Collision Avoidance Based on GPS Position Broadcasts," *Proceedings of the 1996 AIAA/IEEE, Digital Avionics System Conference*, pp. 393-398, Oct. 27-31, 1996.

The current airborne collision avoidance system provides pilots with approximate information on the relative location of nearby traffic and recommended escape maneuvers in the vertical plane. It relies on range measurements and suffers from a high false alarm rate.

This paper studies a new collision avoidance system, which is based on periodic broadcasts of aircraft position as derived by an on-board GPS receiver. Several collision detection algorithms were evaluated by using a Monte Carlo simulation of random encounters in a free-flight environment. The algorithm selected uses the miss distance vector for both detection and

avoidance. This approach can significantly improve the effectiveness of the current collision avoidance system while lowering both the probability of false alarm and the probability of late alarm.

Gebre-Egziabher, D., Hayward, R., and Powell, J. D., "A Low-Cost GPS/Inertial Attitude Heading Reference System (AHRS) for General Aviation Applications," *Proceedings of the 1998 IEEE Position Location and Navigation Symposium*, pp. 518-525, Apr. 20-23, 1998.

An inexpensive Attitude Heading Reference System (AHRS) for general aviation applications is developed by fusing low-cost ($20-$1000) automotive grade inertial sensors with GPS. The inertial sensor suit consists of three orthogonally mounted solid state rate gyros. GPS is used for attitude determination in a triple-antenna, ultrashort-baseline configuration. A complementary filter is used to combine the information from the inertial sensors with the attitude information derived from GPS. The inertial sensors provide attitude information at a sufficiently high bandwidth to drive an inexpensive glass-cockpit type display for pilot-in-the-loop control. The low-bandwidth GPS attitude is used to calibrate the rate gyro biases on-line. In a series of ground and flight tests, it was shown that the system has an accuracy better than 0.2 degree in yaw, pitch, and roll. Data collected during laboratory testing are used to construct error models for the inertial sensors. Analysis based on these models shows that the system can coast through momentary GPS outages lasting 2 minutes with attitude errors less than 6 degrees. Actual performance observed during ground and flight tests with GPS off was found to be substantially better than that predicted by manufacturer supplied specification sheets. Based on this, it is concluded that off-line calibration combined with GPS based in-flight calibration can dramatically improve the performance of inexpensive automotive grade inertial sensors. Data collected from flight tests indicate that some of the automotive grade inertial sensors (180 deg/hr) can perform near the low end of tactical grade (10 deg/hr) sensors for short periods of time after being calibrated on-line by GPS.

Gorder, P. and Uhlarik, J., "The Role of Automation in the Integrated Cockpit of Tomorrow's General Aviation Aircraft," *Proceedings of the IEEE International Conference on System, Man, and Cybernetics 1995, Part 5 of 5*, pp. 4196-4200, Oct. 22-25, 1995.

In the past 25 years, the general aviation (GA) industry has declined significantly. The National Aeronautics and Space Administration (NASA) has implemented the Advanced General Aviation Transport Experiments (AGATE) program, demonstrating its commitment in reviving the industry. The goal of this program is to incorporate new and emerging technologies into the development of an affordable, safer, and easier to fly GA aircraft. Recent technological advances, in particular, innovative use of global positioning system (GPS) based sensors, have made possible the development of affordable, highly automated flight systems. Depending on automation alone, however, without very careful assessment of human factors could very well complicate, rather than simplify, the flight operations. To achieve AGATE's goal will require additional research to ensure that the technological advances are put to the most advantageous use in the development of an appropriate integrated cockpit for the GA application.

Hatfield, F., Jenkins, E., Jennings, M., and Calhoun, G., "Principles and Guidelines for the Design of Eye/Voice Interaction Dialogs," *Proceedings of the 1996 3rd Annual Symposium on Human Interaction With Complex Systems*, pp. 10-19, Aug. 25-28, 1996.

Pilots and operators of advanced military systems need better ways of interacting with their systems, including more efficient human-machine dialog and better physical interface devices and interaction techniques. The goal of the Eye/Voice Mission Planning Interface (EVMPI) research is to integrate voice recognition and eye-tracking technology with aviation displays in order to reduce the pilot's cognitive and manual workload. In its current state of development, the EVMPI technology allows an operator to gaze on user interface items of interest and issue verbal commands/queries that can be interpreted by the system; thus permitting hands-free operation of cockpit displays. This paper describes the concept for the EVMPI, presents general principles for integrating eye gaze and voice input in the form of human-computer interaction dialogs, and describes the architecture and current implementation of the system.

Hayward, R., Gebre-Egziabher, D., Schwall, M., Powell, J. D., and Wilson, J., "Inertially Aided GPS-Based Attitude Heading Reference System (AHRS) for General Aviation Aircraft," *Proceedings of the 1997 10th International Meeting of the Satellite Division of the Institute of Navigation*, Vol. 1, pp. 289-298, Sept. 16-19, 1997.

GPS was used with ultrashort baselines (two to three carrier wavelengths) in a triple-antenna configuration to obtain attitude for general aviation (GA) aircraft. Through algorithm selection and error source calibration, accuracies of 0.1°, 0.15°, and 0.2° rms were obtained for pitch, roll, and yaw respectively. The accuracy and robustness of the system was enhanced by combining the ultrashort-baseline GPS attitude solution with an attitude solution derived using inexpensive automotive grade rate gyros. The solid state gyros allow coasting through temporary GPS outages lasting 2 minutes with attitude errors less than 6 degrees. The combined GPS-inertial system has a 20-Hz output sufficient to drive glass-cockpit type displays. A prototype system was built and flight tested in a Beechcraft Queen Air. The system installed and flight tested in the Queen Air compares favorably to the performance of the existing vacuum driven instruments. It is currently being used in ongoing research at Stanford with futuristic high resolution displays.

Hettinger, L., Cress, J., Brickman, B., and Haas, M., "Adaptive Interfaces for Advanced Airborne Crew Stations," *Proceedings of the 1996 3rd Annual Symposium on Human Interaction with Complex Systems*, pp. 188-192, Aug. 25-28, 1996.

This paper discusses several general research and development issues that the authors view as critical to the design of adaptive interfaces for future US Air Force crew stations. Its major intent is to propose and describe three classes of variables and events that are considered to be potentially useful triggers for the introduction of functional adaptations to crew station displays and controls. These include the interdependent categories of external-environmental events, internal-physiological events, and behavioral events. This discussion is intended to describe an approach to the development of adaptive interfaces being pursued within the US Air Force Armstrong Laboratory's Human Engineering Division and evaluated within the the Synthesized Immersion Research Environment (SIRE) Facility. It is also intended to stimulate discussion and

debate on the nature of factors that might reasonably be expected to reliably drive the dynamic processes that can adapt interfaces in real time to enhance the human use of complex tactical aviation systems.

Ko, P., Enge, P., and Powell, J. D., "Continuity Improvements via Intertial Augmentation of GPS-Based Landing System," *IEEE Position Location and Navigation Symposium*, pp. 153-160, April 22-26, 1996.

The role of inertial backup of GPS-based landing systems in the improvement of continuity is investigated. The purpose is to understand the relationship between the grade of inertial system and the system accuracy during various GPS discontinuity scenarios. GPS outages are considered at various locations on the approach. For systems that included pseudolites (PL's), outages are considered before entering the PL range of coverage (the bubble) and after exiting the bubble. The inertial systems are assumed to be calibrated by GPS during the en route portion of flight. Linear covariance analysis and Monte Carlo techniques are used to determine the navigation accuracy at the runway threshold to determine whether the system meets the various levels of Required Navigation Performance (RNP).

It was found that in the event of a total loss of satellite GPS signals prior to bubble entrance, a navigation grade INS could be calibrated by three suitably placed PL's sufficiently accurate to provide a RNP that allowed the most stringent landing minimums (Category III). Other less drastic outage scenarios all indicated that substantial improvements in continuity can be achieved with inertial system augmentation. Except for GPS outages within 50 seconds of touchdown, navigation grade inertial systems were required for useful improvements. Conditions that allow tactical missle grade inertial systems for CAT-III RNP for the case of a GPS outage within 50 seconds from touchdown are specified.

Lawrence, D., Cobb, H., Cohen, C., Christie, J., Powell, J. D., and Parkinson, B., "Maintaining GPS Positioning in Steep Turns Using Two Antennas," *Proceedings of the 1995 8th International Technology Meeting of the Satellite Division of the Institute of Navigation, part 2 of 2*, pp. 1451-1459, Sept. 12-15, 1995.

Satellite availability studies commonly assume a fixed-elevation mask angle. However, as an aircraft banks, relatively high satellites can be masked from the field of view of the GPS antenna. Not only are fewer satellites visible, but those that are in view are clustered in one section of the sky. This geometry typically leads to high Position Dilution of Precision (PDOP). During steep turns, this effect can limit the availability of GPS and wide-area augmentation system (WAAS) satellites, especially at high latitudes. However, if a second GPS antenna is installed on the aircraft, satellites masked from the main antenna may still be used. This paper presents experimental results of kinematic GPS positioning using two antennas.

The Integrity Beacon Landing System (IBLS) developed at Stanford University uses a bottom GPS antenna to acquire pseudolite signals. Attitude is provided to account for the moment arm from the top antenna to the bottom antenna. With a bottom antenna and attitude already

available, the IBLS test aircraft required few changes to demonstrate GPS positioning using multiple antennas.

A nine-channel Trimble receiver with an RF section dedicated to each of the two antennas was used for these tests. Each channel could switch between the top and bottom antennas as required to track the desired satellite. The switches were performed using attitude information provided by a separate GPS attitude receiver. Satellites were handed off from one antenna to the other in real time as the aircraft attitude changed.

Experiments were first performed using a model aircraft on the ground. Flight tests were then performed on a Piper Dakota already equipped for IBLS testing. The results of these tests show that multiple GPS antennas can be used effectively to improve the availability of GPS positioning.

Lawrence, D., Cobb, S., Pervan, B., Cohen, C., Enge, P., Powell, J. D., and Parkinson, B., "Augmenting Kinematic GPS With a Pulsed Pseudolite to Improve Navigation Performance," *Institute of Navigation, Proceedings of the 1996, National Technology Meeting*, pp. 537-545, Jan. 22-24, 1996.

The stringent availability and continuity requirements for precision approach and landing are difficult to achieve using unaugmented local area differential global positioning system (DGPS). Even more severe is the requirement on integrity. However, to check the integrity of a GPS position solution with Receiver Autonomous Integrity Monitoring (RAIM), more than four ranging sources are needed. Therefore, to meet all of the Required Navigation Performance (RNP) parameters, it may be necessary to augment the GPS constellation with additional ranging sources. Such an augmentation may be achieved by placing a ground-based GPS transmitter (pseudolite) at or near the airport.

To show the navigation performance improvements offered by pseudolite augmentation, flight tests were performed in a Piper Dakota. A pseudolite was placed at the airport and was pulsed to eliminate the near-far problem. The pseudolite signal was used as an additional ranging source to demonstrate the following tasks:

- Centimeter-level positioning accuracy with only three satellites.
- RAIM-based fault detection with only four satellites.
- Single-channel fault isolation with only five satellites

These results show that a pulsed pseudolite can provide an additional kinematic ranging source to an aircraft on final approach. This low-elevation precision ranging source has the potential to greatly improve the navigation performance offered by a local area DGPS system. This paper presents the results of preliminary flight tests incorporating pulsed pseudolite augmentation.

Lawrence, D., Evans, J., Chao, Y., Tsai, Y., Cohen, C., Waiter, T., Enge, P., Powell, J. D., and Parkinson, B., "Integration of Wide Area DGPS with Local Area Kinematic DGPS," *IEEE 1996 Position Location and Navigation Symposium*, pp. 523-529, April 22-26, 1996.

The Stanford University Wide-Area DGPS network has provided a test bed for the development and evaluation of Wide-Area Augmentation System (WAAS) algorithms. Until recently, the accuracy performance of these algorithms was assessed only for static users and users on the ground. The only truth models available relied on the user being at a known location or on a surveyed runway. To remedy this situation, the WAAS system was integrated with the Integrity Beacon Landing System (IBLS). IBLS is a local area kinematic DGPS system capable of providing centimeter-level positioning accuracy. The accurate trajectories provided by IBLS are used to assess WAAS performance in an airborne environment.

The integration was achieved by porting both the IBLS user software and the WAAS user software to a real-time multiprocessing operating system. Both systems now run simultaneously as separate processes on a single computer. The processes can communicate with each other for real-time comparison. They also store data to allow more detailed evaluation in post-processing. Results of flight tests of the Stanford WAAS network are presented.

The integration of WAAS with IBLS provides more than just positioning truth for WAAS tests. The transition from en route navigation to precision approach and landing can now be explored. Results of flight tests demonstrating this transition will be presented in a future paper.

McLean, D. and Zouaoui, Z., "An Airborne Windshear Detection System," Vol. 101, No. 1010, pp. 447-456, Dec. 1997.

For a long time there has been growing awareness in the international aviation community of the considerable danger which an encounter with the atmospheric phenomenon of windshear can bring to an aircraft in flight. Considerable statistical evidence is now available which points to the fact that aircraft windshear encounters in initial climb, final approach, or landing are extremely hazardous, often leading to fatal accidents. The paper presents details of a preliminary design for an airborne windshear detection system suitable for use in general aviation aircraft. First, an elementary explanation of windshear and its most dangerous form, the microburst, is given together with a short account of the hazards that such atmospheric phenomena can present to aircraft in flight, particularly at takeoff and landing. Then a novel windshear detection algorithm is described and associated simulation results are presented. The algorithm is based upon observer theory and uses only a restricted number of measurements. The system is shown to provide very good estimates of the horizontal and vertical components of some windshear encounters. These estimates of the windshear components are then used to provide the pilot with a warning of the presence of windshear together with an indication of its severity. Digital simulation has been used to show the effectiveness of the proposed design.

Mortimer, R., "Some Factors Associated with Pilot Age In General Aviation Crashes," *Proceedings of the 6th International Symposium on Aviation Psychology*, p. 800, April 29-May 2, 1994.

A sample of 1034 NTSB Accident Brief reports for 1985/86 were analysed to discern age differences of pilots in the characteristics of general aviation airplane accidents. Pilots aged 60 or more were more involved in taxiing accidents and those under 30 more in the maneuvering

phase. In combination with pilot exposure data from another study and FAA accident data for 1986, the accident rates of pilots aged 60 or more and younger pilots were estimated. Those aged 60 or more had an accident rate about twice that of the younger pilots.

Mortimer, R., "General Aviation Airplane Accidents Involving Spatial Disorientation," *Proceedings of the 39th Annual Meeting of the Human Factors * Ergonomic Society, part 2 of 2*, pp. 25-29, Oct. 9-13, 1995.

National Transportation Safety Board accident data for 1983-1991 were used to compare those general aviation accident cases that involved spatial disorientation (SD) with all others. About 2.1% of general aviation airplane accidents involved SD. Those accidents were associated with low ceilings, restricted visibility, precipitation, darkness, and instrument night conditions. Pilots in certain professions, particularly those in business, were more involved in SD accidents. Pilots in SD accidents were more often under pressure, fatigue, anxiety, physical impairment, and alcohol or drugs. The pilots' total and night flying experience were inversely related to involvement in SD accidents. Spatial disorientation accidents accounted for a small number of crashes, but they were very severe—fatalities occurred in 92%, they accounted for 9.9% of the fatal accidents, 11% of the fatalities and in 95% the aircraft were destroyed. The results suggest that the pilots in SD accidents lacked the flight experience necessary to recognize or cope with the stimuli that induce SD, which was compounded by fatigue, alcohol/drugs or pressure, and other psychological and physical impairments. Specific exposure to conditions leading to SD in training of general aviation and all pilots should be evaluated to help them to recognize it, and the techniques used by experienced pilots to combat its onset and effects should be studied and used in training. Improved human factors engineering of the cockpit instrumentation is also needed.

Ray, R., Hicks, J., and Wichman, K., "U.S.A. Real-Time In-Flight Engine Performance and Health Monitoring Techniques for Flight Research Application," *Proceedings of the 16th Symposium Aircraft Integrated Monitoring Systems*, pp. 311-340, Sept. 17-19, 1991.

Procedures for real-time evaluation of the in-flight health and performance of gas turbine engines and related systems have been developed to enhance flight test safety and productivity. These techniques include the monitoring of the engine, the engine control system, thrust vectoring control system health, and the detection of engine stalls. Real-time performance techniques were developed for the determination and display of in-flight thrust and for aeroperformance drag polars. These new methods were successfully demonstrated on various research aircraft at the NASA Dryden Flight Research Facility. The capability of NASA's Western Aeronautical Test Range and the advanced data acquisition systems were key factors for implementation and real-time display of these methods.

Seth, S. and Crabill, N., "Pilot Weather Advisor System," *Journal of Aircraft*, Vol. 31, No. 6., pp. 1240-1243, Nov.-Dec. 1994.

A system called the Pilot Weather Advisor (PWxA) is currently under development. This will provide pilots with graphical weather depictions using color laptop computers and eventually

will be a part of an advanced technology flight management system. Through the use of broadcast satellite communications, the PWxA system provides near real-time graphic depictions of weather information in the cockpit of aircraft in flight. The purpose of this system is to improve the safety and utility of general aviation and commercial aircraft operations. The concept of providing pilots with graphic depictions of weather conditions, overlaid on maps with geographical and navigational information, is extremely powerful. We have demonstrated the feasibility of using satellite communications to provide significant amounts of weather data to aircraft in flight. We have also demonstrated the usefulness of providing weather data in graphic form, which increases efficiency and decreases pilot workload.

Schutte, P. and Willshire, K., "Designing to Control Flight Crew Errors," In *Proceedings of 1997 IEEE International Conference on Systems, Man, and Cybernetics*, pp. 1978-1983, Oct. 1997.
It is widely accepted that human error is a major contributing factor in aircraft accidents. There has been a significant amount of research in why these errors occurred, and many reports state that the design of flight deck can actually dispose humans to err. This research has led to the call for changes in design according to human factors and human-centered principles. The National Aeronautics and Space Administration's (NASA) Langley Research Center has initiated an effort to design a human-centered flight deck from a clean slate (i.e., without constraints of existing designs.) The effort will be based on recent research in human-centered design philosophy and mission management categories. This design will match the human's model of the mission and function of the aircraft to reduce unnatural or nonintuitive interfaces. The product of this effort will be a flight deck design description, including training and procedures, and a cross reference or paper trail back to design hypotheses and an evaluation of the design. The present paper will discuss the philosophy, process, and status of this design effort.

Shoucri, M., Davidheiser, R., Hauss, B., Lee, P., Mussetto, M., Young, S., and Yujiri, L., "A Passive Millimeter Wave Camera for Aircraft Landing in Low Visibility Conditions," *IEEE Aerospace and Electronic System Magazine*, Vol. 5, No. 5, pp. 37-42, May 1995.

Fog and low-visibility conditions have hampered aviation since its inception. Fog-related accidents are numerous, and canceled takeoffs and landings due to fog and low-visibility conditions (Cat III) have significant economic impact on airlines, parcel carriers, and general aviation. Millimeter waves have good propagation properties in weather and give adequate spatial resolution when used to image the forward scene. Passive millimeter wave focal plane array cameras are new sensors which, integrated into future guidance and landing systems, promise to be an effective aid, or alternative, to existing technology for aircraft landings and takeoffs under Cat III conditions. They can produce visual-like radiometric images at real-time frame rates (up to 30 Hz) and are directly amenable to image fusion with infrared and visible images. TRW has been actively involved in developing and productizing this technology both at the hardware and the system levels.

Thompson, J., "Aircraft/Control System Simulation," *Proceedings of the 1996 IEEE International Conference on Control Applications*, pp. 119-124, Sept. 15-18, 1996.

This paper describes an aircraft/control system simulation facility being developed at Kansas State University as part of a National Science Foundation (NSF) "Flexible Embedded Control System Design" laboratory project. The simulation facility will support teaching and research in the design of new and innovative flight control systems for general aviation aircraft. In cooperation with representatives of the aviation industry we have proposed an Advanced General Aviation Flight System (AGAFS) based on a hybrid array of flight sensors and actuators and the application of stability augmentation and flight control concepts. The proposed system includes a navigation and pilot information system based on Global Positioning System (GPS) and data link technology and a Health Monitoring System (HMS). The purpose of the simulation facility is to provide the capability where designs of this advanced flight system can be evaluated both as individual system elements and as part of the overall system including pilot-in-the-loop studies. As the design progresses and prototypes of the hardware are built, the simulation will permit inclusion of these hardware modules in place of the simulation code.
The paper describes the following capabilities which are included in the simulator:

- Modules for each of the systems, sensors, and actuators of the AGAFS.
- Coordinate System definitions and transformations.
- Multidimensional nonlinear function interpolation algorithm.
- Numerical Integration of the Aircraft Rigid-Body Equations of Motion.
- Atmospheric density, speed of sound, and sigma model.
- Local wind velocity and turbulence model.
- Real-time position, velocity, and signal characteristics of the constellation of GPS satellites.
- Ground scene generation and display (projection).
- Cockpit instrumentation and "heads-up" display (projection).
- Aircraft data for a variety of flight conditions.
- Hardware interface.
- Real-time operating system.
- Cockpit with appropriate controls and displays.

The implementation of the simulator is on a Sun, Sparc 20, workstation with a ZX graphics accelerator and a 120-MHz Pentium PC connected by a high-speed instrumentation bus (IEEE 488). The Sun workstation is used to simulate aircraft dynamics, the GPS satellite information, the atmosphere, and the ground scene; and the PC is used to simulate the real-time instrumentation, control, and display systems. This unique combination will permit us to maintain strict real time in the control system with a very powerful computational system without

the large hardware and software costs associated with the development of large multi-processor or super-computer systems. The PC will house data acquisition and control boards which will permit the integration of real hardware components into the system as the control system develops.

The simulation adheres rigidly to the terminology and definitions of the "Recommended Practice for Atmospheric and Space Flight Vehicle Coordinate Systems," the ANSI Standard developed by the American Institute of Aeronautics and Astronautica (AIAA) and borrows several concepts from LaRCsim a Workstation-based generic flight simulation program developed and distributed by the NASA Langley Research Center.

Wickens, C. and Battiste, V., "Cognitive Factors in Helicopter Low-Level Navigation: An Overview of the Research," *American Helicopter Society, Proceedings of the 50th Annual Forum, Part 1 of 2*, pp. 139-146, May 11-13, 1994.

A set of seven experiments are described that examine cognitive factors involved in low-level navigation and how these factors are influenced by electronic map display design. In the first four experiments, issues of map rotation are addressed. In addition to their technical costs in graphics requirements, rotating maps also provide the pilot with an inconsistent representation of the terrain, which may hinder the performance of certain map location tasks. However rotating maps also provide a congruence between the map depictions and the forward field of view and control action while on southerly headings. This congruence is missing from fixed north up maps. Our results suggest that the benefits of map rotation are indeed task dependent and that both visual momentum principles and workload sharing by a second crew member may offset the navigational costs of fixed maps. In two experiments, the feasibility of 3D (perspective) maps was examined. The results suggest that these should be track up, that they support adequate lateral guidance, but do not provide as effective support for vertical control. The final experiments examine methods of flight rehearsal. Map study is compared with passive viewing of videos and active flying through computer generated imagery of the path to be flown. Active flight is the superior technique when workload is low but diminishes in effectiveness under high workload. Map study appears to be quite effective in both experiments.